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Boris S. Sokolov
Academician, Russian Academy of Sciences
Counsellor of the Presidium of the Russian Academy of Sciences

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Dear Nikolai Sergeevich!

A. L. Yanshin

Presidium of the Russian Academy of Sciences, Division of Geology, Geophysics, Geochemistry, and Mining Sciences, Leninskii pr. 32, Moscow, 177993 Russia

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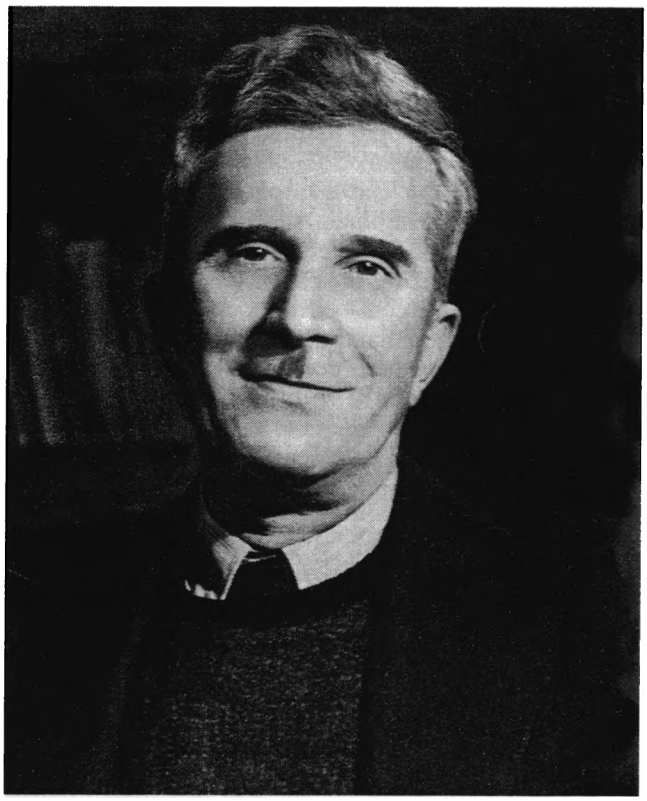

"Dear Nikolai Sergeevich!" Both the disciples and colleagues of Nikolai Sergeevich Schatsky addressed him in this manner. Kind, always smiling and witty, he, in fact, was dear to everybody who was acquainted with him. However, he was also persistent and even forceful in his beliefs.

Schatsky is rightly considered to be a head of the Moscow tectonic school, which gave a start to many prominent researchers. At the same time, he was a scientist with a broad spectrum of interests that allowed him to make outstanding empirical discoveries in both stratigraphy and lithology.

His way into science was quite unusual. He was born in Moscow on August 28, 1895, into the family of a bookkeeper, who worked at one of the large factories. After graduating from Moscow gymnasium no. 10, he became a student at Moscow University in the Natural Division of the Faculty of Physics and Mathematics. At that time, lectures on geology were given there by prominent scientist Alexei Petrovich Pavlov. However, because of World War I, Schatsky did not finish his education. In August, 1916, he joined the Field Army, and after training in warrant officer school, served in this rank in the 55th Infantry Regiment until demobilization in April, 1918, after the October Revolution.

At that time, the High Council of the National Economy decided to organize the Mining Academy, and in December, 1918, Schatsky, on Pavlov's suggestion, began giving lectures on geology. However, this work lasted less than one year. In the summer of 1919, he was again mobilized, this time, with the Red Army. At the beginning of 1921, he was released from duty and turned back to his work at the Mining Academy. During the first two years, he worked as an assistant to the Chair of General Geology headed by Pavlov. Later, he was responsible for working with students on paleogeography and paleontology as an assistant to Professor G.F. Mirchink, who delivered lectures on historical geology. Beginning in autumn, 1924, he assisted Professor A.D. Arkhangel'skii, who gave lectures on the geology of the USSR. At first, Schatsky delivered lectures on only a limited number of topics, but after two years, he lectured on the geology of Siberia and the Far East. While preparing his lectures, he became acquainted with all of the available literature on the geology of eastern Russia, which led him to draw some new conclusions which he later discussed in his special papers.

His friends joked that he performed a professor's responsibilities while having no diploma in higher education. Therefore, he took an external degree in the Mining Academy, and in the spring of 1929, received a diploma in mining geology.

In autumn, 1929, Communist Party leaders decided on a course for country industrialization, which effec-

tively caused the reorganization of the Moscow Mining Academy. It was divided into several independent institutes: the Mining Institute, Petroleum Institute, Institute of Peat, Institute of Steel, and Institute of Non-Ferrous Metals. Its faculty of prospecting geology was joined with the faculty of geology of Moscow University to form the new Moscow Geologic-Prospecting Institute.

During the winter of 1929 - 1930, Schatsky began, for the first time in Russia, lecturing on tectonics and structural geology. However, he considered the subject of geology of the USSR to be more important and interesting, and in the autumn of 1933, Arkhangel'skii recommended him to lecture on this topic. In addition, Schatsky was a supervisor of the diploma theses for undergraduate students and for graduate candidate dissertations. This gave hundreds of geologists throughout the country the chance to consider themselves to be his disciples (Shantser, 1985).

In addition to his pedagogical activity, Schatsky performed extensive scientific investigations. At the very beginning of the 1920s, he cooperated with the Main Coal Committee of the High Council of the National Economy by studying coal deposits in the Moscow Basin and conducting a detailed geological survey in different areas of this region. In summer, 1922, Arkhangel'skii invited him to work in the geological department of the newly organized Research Commission on the Kursk Magnetic Anomaly and to study the Upper Cretaceous deposits in the northern margin of the Donets Basin.

From 1924, his investigations were continued in eastern Ciscaucasia and Azerbaidzhan, where he worked as a mapping geologist for various oil organizations. This work provided the materials for a number of his publications (Menner and Schatsky, 1927; Schatsky, 1927, 1928, and others), and continued until 1932. Meanwhile, in 1931, Schatsky visited Lake Baikal to consult the local mapping geologists in the Buryatiya region (Ryabukhin, 1973). In 1933, he consulted the prospecting works on the salt-bearing deposits in the Bakhmut depression with the aim of estimating the potential of obtaining helium from the Carboniferous-Permian boundary strata underlying the salt member.

In 1934, Schatsky participated in studies on the stratigraphy, tectonics, and coal deposits in the Bureya depression of the Far East. In doing so, he extended his knowledge on the geology of different regions of Russia.

In that same year, a decision was made to transfer the Academy of Sciences from Leningrad to Moscow. Academician Arkhangel'skii, who was invited to head the Geological Institute, suggested Schatsky to organize the department of tectonics at the Institute. From that time, the scientific activity of Schatsky for almost a quarter century was closely connected with this institute, where he gathered a large team of young talented scientists who worked with enthusiasm under his leadership.

Because of their sharp criticism of some outdated ideas, these young scientists were called by old geologists "the gang from Zamoskvorech'e" (Zamoskvorech'e is an area in Moscow, where the Geological Institute is situated), with Schatsky as its "chieftain."

However, the atmosphere in this "gang" was creative, and many its members later became prominent scientists. Among those who worked in the tectonic department of the Geological Institute in the 1930 - 1940s, were future Academicians R.G. Garetskii, A.L. Knipper, Yu.A. Kosygin, P.N. Kropotkin, A.V. Peive, Yu.M. Pushcharovskii, and A.L. Yanshin, and Corresponding Members of the Russian Academy of Sciences N.A. Bogdanov and Yu.G. Leonov.

The first publications of Schatsky dealt with the problems of regional geology in the lower Volga River region, northern Donets Basin (Schatsky, 1923, 1924, 1924), Ciscaucasia, and in the oil-bearing areas of Azerbaidzhan. The problems of stratigraphy and tectonics also received equal emphasis in these papers. In one paper dedicated to the Upper Cretaceous deposits of the northern Donets Basin, Schatsky (1924) described a new variety of the *Ostrea* species. Simultaneously, while conducting regional studies, Schatsky always made conclusions of theoretical significance. For instance, while tracing the thickness changes of separate members in the coal-bearing deposits of the Donets Basin, he concluded that the formation of anticlines and synclines observed here commenced during the Carboniferous, concurrently with sedimentation, and was not the result of the consequent compression only.

In 1924, the monograph "Grundfragen der fergleichenden Tektonik" (Main Problems of Comparative Tectonics) by Hans Stille, a prominent German geologist, was published in Berlin. It was stated in this monograph that, in general, all deformations of initial rock occurrence, not only the folding, took place during short tectonic phases, and each of the 22 phases recorded in the earth's Phanerozoic history was of planetary scale.

Despite its metaphysical character, this "canon of tectonic phases" received wide acceptance in all countries but France. In Russia, it was advertised in N.M. Strakhov's special paper and was used in stratigraphic studies, often contradicting paleontologic data. The terms "Pyrenean phase," "Austrian phase," and "Savian phase" started to appear in geological literature in the late 1920s and early 1930s. Because every phase was thought to be of global scale, the angle discordances were used to correlate geological sequences in distant regions. Soon, it appeared that the number of tectonic phases defined by Stille was insufficient, and needed to be completed with additional phases. For instance, M.A. Usov recognized 32 new tectonic phases in the Altai Mountains alone.

In this new aspiration, Schatsky immediately recognized the revival of the catastrophism ideas of the early 19th century and strongly opposed it. In a series of his papers, he argued that the formation of fold structures,

even within the same tectonic region, occurred slowly and asynchronously (Schatsky, 1937b, 1939a, 1951, and others). In his later works, Stille himself rejected his "canon of tectonic phases," which is now out of use.

At the end of the 1920s, Schatsky published articles on the tectonics of the Tertiary structures in northeastern piedmonts of the Caucasus (1927), Paleogene stratigraphy of the eastern Caucasus (Menner and Schatsky, 1927), and on facies and oil-bearing potentials of the Maikop deposits in the latter region. In addition, in these years he also issued a monograph dedicated to the geological structure of the eastern part of the Chernye Mountains in Daghestan, a synopsis on Cenomanian and Paleogene phosphorites of the Dnieper–Donets trough, and a very interesting paper where the possibility of using such rocks as opoka and tripoli as adsorbents in the oil-refinery industry was considered (Schatsky and Khokhryakova, 1926). This discovery allowed the country to organize the local production of attapulgite, which was previously imported.

In 1931, Schatsky published, among other works, an important article titled "Origin of the Romny Gypsum and Rocks of the Isachkov Hill in Ukraine" (Schatsky, 1931). While the outcrops of gypsum near the city of Romny and diabase rocks at the Isachkov Hill were known for a long time, Schatsky was the first to explain their exhumation at the day surface by the activity of salt diapirs in the Dnieper–Donets depression. By virtue of the fact that similar rocks, which in western Kazakhstan and Texas associate with salt, contain oil deposits, Schatsky predicted their discovery in this region. The drilling which initiated after this article was published confirmed his prediction. Oil deposits were discovered in Romny, as well as in many other areas of the Dnieper–Donets depression (Lapkin, 1973).

In 1932, Schatsky issued a large summary titled "Main Features of Tectonics of the Siberian Platform" (Schatsky, 1932). The point of the paper was that the belt of metamorphozed rocks and granites stretching from the Stanovoi Range via the ranges of the Baikal and Transbaikal regions to the Sayany Range, and further to the mountains of northern Mongolia, were thought to represent the most ancient structural element of Siberia. Resting upon the earlier observations of I.D. Cherskii (1886), Eduard Suess in his fundamental work "Das Antlitz der Erde" named this belt "the ancient crown of Asia." Academician V.A. Obruchev, the best-known researcher of Siberian geology, using the formerly accepted terminology by Serge Bubnoff, classified "the ancient crown of Asia" as "the continental block of the first order" similar to the Baltic shield, and termed the Siberian platform "the shelf" (Obruchev, 1927).

In his article, Schatsky clearly illustrated that the Siberian platform, with its old metamorphozed basement, should be considered as the most ancient structure of northern Asia, whereas the orogenic structures of "the ancient crown of Asia" are younger and formed because of orogenesis, which occurred at the very end of the Precambrian.

Schatsky definitely outlined the boundaries of the Siberian platform as they are accepted today, suggested the first division of its vast territory into tectonic areas, and described its major structural elements: the northern Siberian block (now called the Anabar massif), Aldan block, Lena–Vilyui and Khatanga depressions, "Lena–Enisei Cambrian-Silurian field," Tunguska Basin, and Jurassic coal-bearing depressions, the latter stretching in the form of a narrow belt along the East Sayany Range piedmont. The fold structures fringing the Siberian platform in the east, south, and southwest were described by Schatsky in similar detail. Since the Mesozoic folding phase was not recognized then as a separate phase, the fold structures of the Verkhoyansk Range were considered by Schatsky to be formed as a result of the Laramian orogeny, i.e., he referred them to the Cretaceous-Paleogene.

The fold structures of the Baikal region, in Schatsky's opinion, were formed at the very end of the Precambrian and, probably, during the earliest Cambrian. He proposed this phase to be named the Baikalian folding phase.

Later discoveries of patches of sedimentary rocks with faunal remains of Cambrian-Ordovician age in syncline basins of the Transbaikal region cast doubts on the validity of the Baikalian folding phase. Irkutsk geologists began to advocate that these structures be referred to the Caledonides. However, this viewpoint is unacceptable. The thick conglomerate members of the Ushakovo Formation in the sequences along the Irkut, Olekma, and Goloustaya rivers suggest that some orogenic structure appeared during the terminal Precambrian in the present Baikal region, although Schatsky himself noted a "rather intensive folding process" in this and other areas of Siberia during the Caledonian diastrophism.

At present, the wide distribution of Baikalian fold structures throughout the continents in the Northern Hemisphere and Australia is proven by the many works of M.V. Muratov and other researchers. The Baikalian folding occurred in these places prior to the Vendian, whereas in other areas it took place before the Cambrian. It occurred in the Urals as well, which explains the almost complete absence of Cambrian deposits there and the unconformable contact between different Precambrian strata and Ordovician deposits. According to recent data, nearly everywhere in the Pechora depression and northern Siberian plate the basement was formed during the Baikalian folding.

In 1933, Arkhangel'skii and Schatsky (1933) issued "The Tectonic Scheme of the USSR." It was the first attempt in international geological practice to map in small scale the tectonic areas of main folding phases which terminated the geosyncline development. In eastern Siberia, belts of the Mesozoic folding, which occurred in the Late Jurassic - Early Cretaceous and are

unknown in Europe, were recognized for the first time. In the color map attached to the article, the regions of Mesozoic folding also included the Dobrudzha region, Crimea Mountains, Mangyshlak, Tuarkyr, and the Krasnovodsk Peninsula. The northern Caspian Sea depression, Ustyurt, and left side of the Amu Dar'ya River were shown to be areas with deeply buried Mesozoic folded strata which was not confirmed by later studies. The remaining territories were indicated to represent the regions of pre-Baikalian, Baikalian, Caledonian, Hercynian, and Alpine foldings divided into zones according to the occurrence depths of folded strata. A marginal depression of a different age, strikes of fold axes, swells of the East European platform, and other structures were shown as well.

Based on E.V. Toll's evidence regarding the horizontal occurrence of the Middle Cambrian and Ordovician deposits in Bennett Island, Schatsky distinguished in the considered paper the ancient "plate of the De Long Islands."

Despite the many inaccuracies related to the then insufficient data, the article "The Tectonic Scheme of the USSR" had a profound impact on the development of geological science in Russia, and for a long time predetermined the main tendencies in tectonic research.

In the article "Tectonics of the Arctic," Schatsky (1935) substantiated the existence of the flooded ancient platform of the De Long Islands in detail, and named it the Hyperborean platform.

In the mid-30s, a new direction of Schatsky's activity concerning the history of geological concepts and methods became evident. At that time, the State Publishing House of Biological and Medical Literature was preparing to publish the complete collection of Charles Darwin's works, and Schatsky agreed to be an editor of its 11th volume, which included all of the geological observations of the great English scientist. This volume was issued in 1936 with supplementary chapters written by Schatsky: "Charles Darwin's Geological Observations" (1936a), "Darwin as a Geologist" (1936b), and "Monograph on Fossil Cirripedia" (1936c), as well as his (in co-authorship with L.Sh. Davitashvili) comments printed with a tiny type on 14 pages. These comments also included a brief description of the characteristics of many outstanding scientists of the last century. To write them, one has to be well acquainted with the mode of life and atmosphere of creative work in Darwin's times, with all their ideological, political, and social contradictions.

It should be noted that Schatsky was interested in the history of geological ideas until the end of his life. While he usually analyzed the creative activity of prominent geologists, sometimes he would also publish papers dealing with the history of geologic activity of whole organizations.

After the death of academician Arkhangel'skii in 1940, Schatsky issued a series of articles dedicated to the scientific activity of his old friend as well as a scientific biography, which was published in 1944.

In a series of articles, Schatsky (1947a, 1948a, 1953a, 1958b) discussed different aspects of the scientific activity of A.P. Karpinsky. In Schatsky's opinion, Karpinsky was the first theorist in Russian geology and a supreme expert in geological investigations, who had an important impact on the development of geological sciences well beyond Russia.

While still giving lectures on Siberian geology, Schatsky also concentrated on the scientific activity of academician V.A. Obruchev, the foundator of the Tomsk school of geologists and unexhaustible researcher of remote areas in the Asian part of Russia. Schatsky (1948c, 1950; Schatsky and Pavlovskii, 1956) well demonstrated Obruchev's paramount contribution to investigations of Siberian geology and provided a comprehensive analysis and evaluation of different aspects of his creative activity. Obruchev's multivolume book titled "The History of Geological Investigations in Siberia" was considered by Schatsky to be a manual for every geologist working in this region. Also of interest are Schatsky's articles "Scientific Works of M.S. Shvetsov" (Schatsky, 1958e) and "Role of Academician A.A. Borisyak in Development of Russian Geology" (Schatsky, 1971) issued after his death.

However, Schatsky did not only study the scientific activity of domestic scientists. While analyzing Darwin's works, he became well acquainted with the life of the English scientific community of the middle of the last century. Therefore, in 1940, when the Moscow Society of Naturalists decided for its 135th anniversary to publish commemorative papers devoted to the prominent members of the society, Schatsky readily accepted an invitation to prepare an article dedicated to Roderick Impey Murchison, the English geologist who was elected as a member of the society after his journey through Russia in 1841.

Schatsky quickly completed this work, and in the spring of 1941, his small, but very interesting monograph about Murchison was published. This monograph contained information on the life and scientific activity of this outstanding scientist, analysis of his views and achievements, a description of his journey through European Russia and the Urals, analysis of his main publication (1845) on the geology of the visited areas, and an evaluation of this work regarding its significance for later geological investigations in Russia (Schatsky, 1941).

While preparing the scientific biography of Murchison, Schatsky not only read all of his published works, the full list of which, he attached to the monograph, but also the publications of Archibald Heik, Henri Woodward, and Joseph Prestwich devoted to Murchison as well as his personal correspondence. In the comments attached to the monogragh, he gave brief information about 52 European scientists with whom Murchison met and worked during his life.

Charles Lyell, author of the famous work "The Principles of Geology," ardent opponent of the catastrophism concept, and a creator of the then new paradigm, which was called "the actualism or uniformism principle," was another English scientist who was of great interest to Schatsky. In his publications devoted to Darwin, Schatsky repeatedly mentioned Lyell's name, considered his influence on the development of Darwins's evolutionary concept, and wrote about the debates centered around Layell's views in the London Geological Society, where at first they were discarded. Schatsky planned to write a monograph about Lyell similar to his book devoted to Murchison. Unfortunately, he did not manage to fulfill his intention, and published only two small articles in the *Greater Soviet Encyclopedia* and *Biographic Glossary of Prominent Figures in Natural Sciences and Technics* (Schatsky, 1953b, 1958d).

In the mid-1950s, when Schatsky turned to lithological problems, he was surprised by the variable usage of the term "facies." Therefore, he decided to consult the initial sources and carefully searched all the works of Amanz Gressley, who was the first to introduce this term. At the meeting of the Geological Division of the Moscow Society of Naturalists in May, 1955, Schatsky presented the report "Facies and Formations," in which he discussed Gressley's life and analyzed in detail his works on the geology of the Jurassic Mountains (Arkhipov, 1985). It appeared that Gressley proposed that any significant lateral changes in lithology and paleontologic characteristics of a stratum be called "facies." These changes are always related to changes in sedimentation environments. Gressley defined four laws of the facies distribution, of which the second one is most important. It states that similar facies of two neighboring horizons can have more paleontological characteristics in common than different facies of the same horizon.

Schatsky's lecture devoted to Gressley, titled "Facies and Formations (Gressley and His Theory on Facies)" was published based on the shorthand report (Schatsky, 1965). During his lifetime, Schatsky managed to publish only small notes about the scientist in 1958 in *Biographic Glossary of Prominent Figures in Natural Sciences and Technics* (Schatsky, 1958a, 1958b).

In addition to scientific biographies, Schatsky also issued reviews dedicated to the development of geological knowledge in Russia.

As far back as 1937, he published in the *Byulleten' Mosk. O-va Ispyt. Prir.* an article titled "Twenty Years of Soviet Geotectonics," in which he noted that the first original theoretical works on tectonics began to appear as early as the 1930s. These works, which were based on the analysis of geology in Russia, were important for elaborating the principal scheme of the earth crust structure over the entire territory of the USSR. They also initiated critical revision of West European and American tectonic concepts, and gave rise to new hypotheses explaining the causes and mechanism of tectonic movements. In this article, Schatsky considered that the actual task of scientists was to study data on geology beyond Russia and to generalize available materials on the structure of the entire earth crust and the earth as a whole (Schatsky, 1937d).

In 1945, Schatsky, already elected a Corresponding Member of the Soviet Academy of Sciences (1943), published a large article titled "Development of Geology and Geological Investigations in the Academy of Sciences" (Schatsky, 1945b). In this article, giving tribute to M.V. Lomonosov for being, according to Schatsky, the first theorist in geology, he paid attention to the period of expeditions organized by the Academy in 1764 - 1805. Schatsky also described how at the beginning of the 19th century, the leading role in geological investigations passed to the mining departments of universities, and further, he analyzed the works of K.M. Ber, G.V. Abikh, G.P. Gelmersen, and F.B. Schmidt, and "the epoch of A.P. Karpinskii." The contribution of the latter to the development of geological investigation in the Academy of Sciences was estimated by Schatsky to be very important.

The Soviet period of geological science development was surveyed briefly in the article. However, the author stressed that "the future historians of the Academy of Sciences would designate this period as the new birth of the Academy." Schatsky emphasized as very significant the extensive geological field studies, the organization of new geological institutes, the results of geological investigations carried out by newly born Academies of Sciences in the Soviet Republics, and an unbelievable increase in the number of geological publications. In the almost 200 years of the Academy's existence prior to the revolution, 2150 publications on geology were issued; no less than 10 000 works were published in the 28 years after it.

In 1955, the article "Geological Sciences in the Moscow Society of Naturalists" written by Schatsky (1955b) was published on the occasion of the 150th anniversary of the Society. It was dedicated to the analysis of Society publications on different geological problems and their importance for the geological knowledge in Russia. The enclosed hystogram in the article clearly showed a sharp increase in the number of publications issued by the Society in the 1920s, and this tendency was interrupted for only a short period in the first years of World War II.

As a historian of geological sciences, Schatsky is still insufficiently known (Tikhomirov, 1962). For instance, it was his initiative to organize the special Laboratory on the History of Geological Sciences at the Geological Institute. This laboratory was headed for a long period by V. V. Tikhomirov, who lost his sight during World War II.

The aforesaid does not mean that from the mid-1930s Schatsky turned exclusively to the history of geological sciences. Rather, this was just one aspect of

his scientific activity. Simultaneously, he continued fundamental research on tectonics and stratigraphy.

In 1937, an ominous year, the 17th Session of the International Geological Congress was held in Moscow. Academician A.P. Karpinskii was nominated as Chairman of the Organizing Committee, and after his death (July 15, 1936), the chair was inherited by academician I.M. Gubkin. At the beginning of 1937 Arkhangel'skii, Schatsky and scientists from the Geological Institute prepared and published a special issue titled "Brief Outline of Geological Structure and Geological History of the USSR" and supplemented it with the atlas of paleogeographical maps. In this work, the main focus was the analysis of the history of tectonic movements in both platforms and folded belts in the entire USSR territory and adjacent countries.

In addition, during this session, Schatsky presented two reports: "The Neocatastrophism," in which he sharply criticized H. Stille's concept on planetary short-term tectonic phases, and "Theoretical Front of Geotectonics," in which this concept was compared step by step with the abandoned ideas of Elie de Beaumont, the French catastrophist form the early 17th century. The first of these reports was published in 1937 in the journal *Problemy Sovetskoi Geologii* and the second one in 1939, in the Proceedings of the Congress (Schatsky, 1937b, 1939a).

In 1937, Schatsky and Davydova, published a large paper titled "On the Mesozoic of the Northern Bureya Basin." Schatsky spent the summer of 1934 in this region. In the paper, the authors gave a detailed description of all formations of the basin, specified the stratigraphic succession, and presented evidence that the contact between the Jurassic coal-bearing deposits and granites in the northern part of the basin is normal, but not intrusive. The facies variability of the formations was also outlined to elucidate the basin genesis (Schatsky and Davydova, 1937).

In that same year, which was very productive for Schatsky, his two large articles "Tectonics of the East European Platform" (1937b) and "Origin of the Donets Basin" (1937c) were published in *Byulleten' Mosk. O-va Ispyt. Prir.* With these papers, Schatsky began a series of publications on comparative tectonics of ancient platforms.

As far back as 1936, the Commission of the Academy of Sciences on the Study of Productive Forces organized the Central Kazakhstan Complex Expedition and invited Schatsky to be its chief scientist. To more comprehensively investigate the structures of Central Kazakhstan and to resolve the unclear problems of its Paleozoic and Precambrian stratigraphy, Schatsky organized special groups of geologists to work along three meridional geotraverses: eastern, at the meridian of Karkaralinsk; central, at the meridian of Karaganda; and western, along the boundary with the Tertiary deposits of the Turgai depression.

The first scientific results of the expedition were reported by Schatsky in 1938 in the article "Tectonics of Central Kazakhstan." In this paper, he argued that the folding in the central part of the geosyncline regions remote from ancient cratons is not strictly linear, but repeatedly verging and changing its direction which results in the apparent intersection of the differently oriented folds (Schatsky, 1938). This was previously noted by N.G. Kassin and other geologists. Schatsky concluded that the main folding in northern and western Central Kazakhstan occurred prior to the deposition of the Devonian red sandstones, whereas in the Balkhash Lake region, a typical geosyncline regime continued almost until the terminal Carboniferous, and culminated at the end of the Paleozoic with the Hercynian folding phase, which considerably affected the Caledonian structures in the northern part of Central Kazakhstan. The next period of detailed geological mapping in Central Kazakhstan confirmed all of the principal conclusions of Schatsky.

In 1940, Schatsky issued two additional interesting articles dealing with tectonics of ancient platforms. In one of them, titled "Age of Folded Basement of the Russian Platform" (Schatsky, 1940a), he disputed Arkjangel'skii, who once suggested the Caledonian age of the folded basement in the eastern part of the platform. Schatsky was convinced that the basement age is uniform throughout the platform and corresponds to the Precambrian, which was soon after confirmed by drilling. In his other paper, "Syneclises as Interpreted by A.P. Pavlov," Schatsky recalled that as far back as 1903, Pavlov proposed in one of his small notes that the very flat depressions in platforms be termed "syneclises." This word is composed of two Greek roots meaning "jointly sloping" (Schatsky, 1940b).

Schatsky strongly recommended this term be applied only to those flat depressions, in which dip angles at limbs are measurable in minutes; in other words, angles too small to be measured with inclinatorium. Schatsky pointed out that Moscow and Dnieper–Donets depressions in the Russian platform, or the Tunguska and Vilyui depressions in the Siberian platform well fit the syneclise definition. After this article, the term "syneclise" was included into Russian geological terminology and soon came into use in other countries.

With the beginning of World War II in the summer of 1941, the acute problem of supplying the army with oil products emerged. In this connection, the Academy of Sciences organized the Commission on Resource Mobilization of the middle Volga and Kama regions. Schatsky was in charge of organizing a large team of geologists to study geology and oil potentials in the entire Volga–Urals region.

Besides the aforementioned monograph dedicated to Arkhangel'skii, Schatsky published only one summarizing paper on solid bitumes during the war years (Schatsky, 1943). However, he collected abundant materials for consequent publications, which appeared at the end of

the war. At the beginning of 1945, Schatsky, along with oil geologists, published the paper "Oil Resources of the Second Baku," summarizing the results of his investigations during war time (Schatsky, 1945d). Later, the article titled "Comparative Tectonics of North America and Eastern Europe" was issued (Schatsky, 1945a). It began a series of papers dedicated to comparative tectonics of ancient platforms, namely the following articles: "Main Features of the Structure and Development of the Eastern European Platform" (1946a), "The Great Donets Basin and the Wichita System" (1946b), "On Structural Relations between Platforms and Geosynclinal Folded Regions" (1947a), "Deep Dislocations Affecting Platforms and Foldbelts (the Volga Region and Caucasus)" (1948b), and "The Pachelma Trough Origin" (1955a).

These papers, along with other publications of Schatsky which are not listed here, laid the groundwork for the concept on tectonics of ancient platforms with the Archean or Lower Proterozoic fold basement. Schatsky showed that such platforms are bounded on all sides by linear faults that deeply penetrate into the earth's crust. These faults lend angular shape to the platforms. The adjacent fold structures are usually linear and contact one another along deep faults. Marginal troughs that develop during folding and orogenesis in adjacent geosyncline regions are important tectonic elements of platform fold structures. At the contact with the platform bulge, the marginal troughs fail to develop and are replaced with marginal sutures.

Flat major uplifts within the platforms were proposed by Schatsky to be called anteclises. He established that syneclises represented actively downwarping structures, whereas anteclises represented passive remnant structures and, therefore, strata at their limbs could be variable in age. Schatsky explained the syneclise downwarping by the recrystallization and thickening of deep crustal horizons.

In the article "Troughs of the Donets Type" published posthumously in 1964, Schatsky proposed that such intraplatform troughs with thick dislocated deposits be termed "aulacogens," which in Greek means "born as a furrow." As examples of aulacogens in the Russian platform, he cited the Polish–Danish furrow and Timan Range. This term found acceptance and received wide usage, though in a more broad meaning than suggested by Schatsky. As a result, the usual grabens and rifts are often called aulacogens.

Based on the aforesaid, it may be inferred that Schatsky launched a new theory dealing with ancient platforms and their relationship with adjacent, younger fold structures.

In 1945, when the groundwork of this theory was laid, Schatsky began a new series of fundamental research. At the end of this year, the Moscow Society of Naturalists issued his small monograph "Essay on Tectonics of the Volga–Urals Oil-Bearing Province and Adjacent Western Slope of the Southern Urals" (Schatsky, 1945c). Based on the materials collected during the war years, he described the tectonics of the large territory from the Volga River to the Urals, concentrating mostly on the local uplifts, with which the oil deposits were connected. He suggested that these minor structures be termed "plaqueanteclines" and considered them to have been formed by fault-related movements which was later confirmed by the research of M.A. Kamaletdinov. As a case in point, Schatsky described the Tuimazy uplift. He proposed that irregularly shaped isometric depressions, such as the Melekess depression, be termed "plaquesyneclise." However, both of these terms are rarely used. With this monograph, Schatsky also laid the groundwork for the research of Upper Precambrian stratigraphy. In the western slope of the southern Urals, he studied sections of a large fold structure, which has long been known among the Uralian geologists as the Bashkir anticlinorium. A thick (up to 16 000 m) sedimentary sequence, which is readily divisible lithologically into a series of formations, occurs there. These deposits are locally intruded by diabase dykes, and are unconformably overlain by sandstones of the Middle Devonian Takatin Formation.

Geologists who worked there earlier referred these thick deposits to the Lower Devonian, and some of them believed that they also encompass the Silurian and, probably, some parts of the Lower Paleozoic. Nobody suggested their Precambrian age.

Schatsky called attention to the fact that the rocks composing the Bashkir anticlinorium are barren of fossils and that they are unconformably overlain at the Belaya River left bank in its middle stream by the Middle Devonian and, sometimes, even Lower Devonian strata. From these observations, Schatsky concluded that this abnormally thick sequence of the Baskir anticlinorium is of the Precambrian age, and its upper limit corresponds in time to a major stratigraphic hiatus, which in the Russian platform separates the crystalline basement from the basal strata of sedimentary cover.

Schatsky proposed that the deposits of the Bashkir anticlinorium and their stratigraphic analogues be defined as the Riphean group, and their formation interval as the Riphean era, respectively (after the ancient name of the Urals in works of Herodotos and Strabon).

Later, Schatsky devoted a series of his publications to the Riphean deposits, in which he rightly considered the sequence of the Baskir anticlinorium to represent the standard and most complete one among all Riphean sections. All other Upper Precambrian subdivisions, which were recognized in different countries such as the Infracambrian, Hyperborean, Sparagmian, Sinian System in China, and Vindian System in Indostan, appeared to correspond to the different, mainly upper parts of the Riphean group. Schatsky reasoned that because of the lack of fossils, the methods of tectonics and historical geology should be applied to subdivide and correlate the Upper Precambrian sections. In this

respect, he was mistaken. Initiated during his lifetime on his initiative, the research of algal buildups, i.e., stromatolites and microphytolites, as well as acritarchs showed that traditional biostratigraphic methods are applicable for this purpose with only one adjustment: based on these fossils, it is possible to define longer intervals of geological time than those of the Phanerozoic, which are 250 - 300 Ma long. In 1973, Keller proposed these stratigraphic subdivisions to be named "the phytems."

Schatsky reasoned that the Riphean deposits of the Urals correspond to the complete cycle of tectonic development comparable with any later cycle such as the Caledonian, Hercynian, and Alpine. Three cycles of the second order were defined in the Riphean deposits of the Bashkir anticlinorium, each beginning with quartzites and other clastic rocks overlain by clayey, sometimes flyschoid deposits and thick carbonate formations. However, at the top of the whole cycle, coarse clastic molasse deposits of the Asha Formation occur. Thus, as in younger epochs, the termination of a cycle corresponds to the folding and orogenesis phase. In his works on Siberian geology, Schatsky called this phase the Baikalian folding.

Relying upon geochronological data, we know that Schatsky was right in classifying the Riphean as a group rather than a system. The duration of the Riphean era appeared to be significant. It began at 1700 Ma and terminated at 570 Ma, when the first skeletal marine fauna appeared during the Early Cambrian.

Usually, the latter value was considered to represent the onset of the Paleozoic era. Academician Sokolov (1985) reasonably defined the Vendian period of about 60 Ma long at the end of the Riphean era, and many geologists consider it correct to take this period for the commencement of the Paleozoic era. Still, the inclusion of the Vendian into the Paleozoic casts no doubts on the correctness of Schatsky's conclusion about independence of the Riphean era and, accordingly, the Riphean group.

In his last works, Schatsky (1952a, 1952b) correlated the Riphean sections throughout the Soviet Union. He distinguished them in many regions: the Ukraine Pachelma depression, Byelorussia, Enisei Range, Turukhansk and Olenek uplifts, periphery of the Anabar massif, northern slope of the Aldan massif, localities along the Bol'shoi Patom, Maya, and Yudoma rivers, and the Baikal and Transbaikal (Barguzin–Vitim) regions. Correlation of these huge materials allowed Schatsky to sum up the data on structure and lithology of the Riphean deposits in ancient platforms, mio-, and geosynclines. The results of this correlation were reported in his article "The Principles of Upper Cambrian Stratigraphy and Stratigraphic Range of the Riphean Group" (1960c) and in other works.

It is safe to state now that Schatsky's works on the Riphean era in the earth's history and on deposits of the Riphean group, which were successfully continued at the Geological Institute by M.E. Raaben, I.M. Krylov, M.A. Semikhatov, and their colleagues, gained international recognition and were of a great importance for the development of both domestic and world geology.

Developing the theory of geological formations, Schatsky significantly contributed to lithology. As far back as 1939, he gave the first definition of this term in his small article "Movements and Evolution of the Earth's Crust," which was published in *Sovetskaya Geologiya* (Schatsky, 1939a). In this paper, the geological formation was defined as "a complex of sedimentary and volcanic rocks paragenetically closely related with each other."

During the first 15 years after the war, Schatsky touched upon this problem in many of his works on tectonics and tectonic maps, as well as in papers dealing with the Riphean deposits. The formations and related types of mineral resources were specifically considered in the article "Manganese-Bearing Formations and Manganese Metallogeny" (1954) and the monograph "Phosphoritic Formations and Classification of Phosphorite Deposits" (1955c). In 1960, his interesting comprehensive paper "Parageneses of Sedimentary and Volcanogenic Rocks and Formations" was published. A series of his small notes and oral communications concerning the geological formations appeared posthumously in 1965 in the 3rd volume of his selected works. As a whole, these publications created a new concept on geological formations considered as rock associations often of different genesis but united by the common tectonic and paleogeographic conditions of sedimentation. The definition of "geological formation" in Schatsky's later publications was somewhat different from that given first in 1939. In his last article "Parageneses of Sedimentary and Volcanogenic Rocks and Formations," he considered the latter to represent "the natural rock complexes (assemblages, associations), the individual constituents of which (rocks, members, stratigraphic formations, deposits) are paragenetically related to each other both laterally and in vertical stratigraphic succession" (Schatsky, 1960b).

The originality of the Schatsky definition, which provided for its wide acceptance, was in the idea of considering geological formations as rock paragenesis. This latter term was introduced by him into geological terminology in addition to already existing terms such as "mineral paragenesis" and "paragenesis of chemical elements in minerals." The sense and significance of such a definition, according to Schatsky himself, is in avoiding any hypothetical prerequisites and indicating only the method of study and a place of formations in the general classification of geological bodies.

Schatsky argued that lithologic-genetic complexes represent the initial rock association, whereas the geological formations are combinations of these somewhat similar complexes. The formations form in the platform and geosyneclise settings as natural vertical and lateral

rows. As typical cases in point, he listed flysch, molasses, and paralic coal-bearing formations.

A typical feature of Schatsky's research style was to suggest the verification method of new concepts and definitions introduced. In his works on the manganese- and phosphorite-bearing formations, he emphasized the importance of studying the spatial relationship between the rocks, i.e., the internal structure of geological formations; he also defined the facies rows and facies combinations of rocks, and singled out the "patrimonial" and "allophylic," main and auxiliary members of formations, as well as the "vicariating members of formation rows," and other features.

Whereas the concept on the Riphean era in the Earth's history was at first virtually developed by Schatsky alone, the concept on geological formations acquired followers immediately following his first pertinent publications. This issue became repeatedly discussed by V.V. Belousov, V.P. Kazarinov, V.I. Popov, N.M. Strakhov, P.P. Timofeev, V.E. Khain and many other scientists. Different principles of the formation recognition and their classification were proposed by these researchers. As early as 1953, the first meeting devoted to the problem of geological formations was held in Novosibirsk. Later, this issue became a top priority at a number of All-Union lithological conferences.

At the Geological Institute of the Academy of Sciences, the classical descriptions of certain formations were performed under the leadership of Schatsky by B.M. Keller (1949), I.V. Khvorova (1961), and Z.M. Starostina (1962), but after his death in 1960, this problem gradually disappeared from the scientific programs of the institute. Instead, these works were initiated in the Institute of Geology and Geophysics, the Siberian Branch of the Academy of Sciences. Academician Yu.A. Kuznetsov successfully applied the concept on geological formations to study the magmatic complexes, and his brother, Academician V.A. Kuznetsov used it to discriminate the ore formations close in the time of their origin and united by a common source of ore matter. Academician V.S. Sobolev used the formation method to subdivide sections of metamorphozed rocks. A special laboratory of sedimentary formations, headed by M.A. Zharkov, was organized at the institute. Classical investigations of salt-bearing, phosphorite-bearing, and terrigenous red formations were performed by the scientists at this laboratory. Marine terrigenous formations were studied by researchers from the Laboratory of Sedimentary Rocks headed by Yu.P. Kazanskii. At the All-Union Geological Institute, the leading institute of the USSR Ministry of Geology, the geologists also started to study the geological formations and to compile formation maps. Among the works performed at this institute, the research of geological formations by V.I. Dragunov are especially worth mentioning.

Another of Schatsky's initiatives is also related to the considered concept. In 1953, he addressed the Presidium of the Academy of Sciences with the suggestion to organize special works aimed at investigating regularities in the distribution of various mineral deposits in the earth's crust. He stressed that the surficial geology of the USSR's territory was sufficiently studied and, thus, the epoch of prospecting mineral resources "using the geological hammer" was nearing its end. In the future, one should search the mineral deposits located at deeper levels and unexposed at the day surface. To solve this problem, the general regularities in distribution of various deposits should be investigated using all the available materials, and this should be supplemented with the elaboration of new geophysical and geochemical methods. He specifically emphasized that studies of distribution and not only of the genesis of mineral deposits are of a great importance, because the genesis of deposits even of the same type changed in the course of the Earth's history, and genetical regularities well-established for certain epochs could appear to be invalid for younger or older epochs. Taking into consideration the close relation of many deposits to certain geological formations, he suggested the formation method, among others, to be used for this purpose.

As a result of Schatsky's initiative, the Interdepartmental Commission on the problem "Regularities in distribution of mineral deposits" was organized under his chairmanship. During the subsequent five years, two plenary sessions of the Commission were held and four volumes of its proceedings, which were edited by Schatsky, were issued in 1958 - 1960. In the first of them, Schatsky published the article "Main Directions in Investigating the Problem: Regularities in Distribution of Mineral Deposits in the Earth Crust as a Basis for Their Search in the USSR Territory" (Schatsky, 1958f). In addition, this problem was considered in his articles "Regularities in Distribution of Main Mineral Deposits in the Earth Crust as a Basis for Their Prognosis in the USSR's Territory" (Schatsky *et al.*, 1954) and "Geotectonic Regularities in Distribution of Endogenic ore Deposits" (Schatsky, 1960a).

Now I should dwell on another direction in Schatsky's scientific activity, the tectonic maps.

As was mentioned above, as far back as the 1930s Arkhangel'skii and Schatsky published the first small-scale tectonic schemes of the USSR's territory, and concluded then that the defining ages of major folding phases terminating the geosynecline development is the most convenient method to compile tectonic maps for vast territories. In these maps, the regions where the rocks corresponding to such phases are exposed at the surface, and those where the rocks are unconformably overlain by gently dipping sedimentary strata, should be indicated.

After World War II, the problem of compiling large-scale maps which would show the earth crust's structure at deeper levels became one of the principal issues in Schatsky's scientific activity. Many scientists from the tectonic department which he headed were involved

in compilation of the first tectonic map of the USSR. Many years later, Yu.A. Kosygin, who became a researcher at the tectonic department just after his release from the Field Army in 1945, wrote in his intelligent memoirs: "The scientific team in the department represented a really creative enthusiastic collective, consisting of scientists who thought differently and shared different concepts, but who were strikingly united and complemented each other in the collective, target-oriented work. Schatsky was the soul of this collective, the real generator of ideas, sometimes unexpected and paradoxical, but always intriguing and exciting. He was superior to all of us in briskness and acuteness of mind. This was just fine, because a scientific team always needs a leader, although this chance is not always the case. One can say that this team contributed the golden pages into the development of Soviet tectonics" (Kosygin, 1993, p. 98).

Sometimes, lying on the floor of his large flat among the sheets of paper with different versions of the map, we would discuss the legend for hours, putting in the sites of deep holes and lines of seismic profiles, drawing the stratoisohypses of the basement and reference horizons, and looking through the latest periodical issues, where we could find new tectonic data. By the end of 1951 this work was completed, and in 1953 the first tectonic map of the USSR, the scale 1 : 4 000 000, was published (*Tektonicheskaya Karta* ..., 1953). Directly after the publication of this map, Schatsky, with the same scientific team, began to compile a new, more detailed tectonic map of the USSR. This new "Tectonic Map of the USSR and Adjacent Countries," the scale 1 : 5 000 000, was issued on the eve of the 19th Session of the International Geological Congress held in Mexico (*Tektonicheskaya Karta* ..., 1956). Schatsky could not attend the Congress, and the map was presented by Professor A.A. Bogdanov of Moscow University, one of Schatsky's closest disciples. The participants of the Congress were greatly impressed with this map, and a decision was made to compile tectonic maps of all continents using the method which was elaborated in the USSR. To accomplish this task, it was also decided to organize the Subcommission on Tectonic Maps as a part of the Commission on Geological Maps of the World, whose headquarter was in Paris. Schatsky was invited to preside over this subcommission and to head the works on compiling the tectonic map of Europe. Heads of scientific teams organized for compiling tectonic maps of other continents were also elected during the session.

In 1957, the explanatory notes to the *Tektonicheskaya Karta SSSR i Sopredel'nykh Stran,* which was written by Schatsky and Bogdanov, was published. In 1958, its translations into Chinese and German were issued in Beijing and Berlin, respectively. Somewhat shorter works regarding the new tectonic map of the USSR were published in Spanish in Mexico and in English in Washington in 1957 and 1959, respectively. In 1958, Schatsky's work on compiling the tectonic maps of the USSR was awarded the Lenin Prize.

From the end of 1956, Schatsky worked with enthusiasm compiling the tectonic map of Europe, the scale 1 : 2 500 000, and in this connection, visited France in 1957, 1958, and at the beginning of 1960. He even managed to publish an article about this map (Schatsky and Bogdanov, 1961). By the 21th Session of the International Geological Congress, which was held in Copenhagen at the end of August, 1960, the draft version of the map was completed and the *Explanatory Notes* for it were published in both Russian and English.

However, Schatsky himself could not present the map. Although he had not been ill, early in the morning on August 1, 1960, he suffered a sudden stroke while at his country house. When the ambulance arrived, he was already dead.

He was burried at the "Vvedènskie Gory" cemetery, close to the tomb of his parents. Every year, on August 1, his disciples visit the cemetery, though their number becomes increasingly less each year.

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REFERENCES

Arkhangel'skii, A.D. and Schatsky, N.S., Schemes of Tectonics of the USSR, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1933, vol. 11, no. 4, pp. 323 - 348.

Arkhangel'skii, A.D., Schatsky, N.S., Menner, V.V., *et al.*, *Kratkii Ocherk Geologicheskoi Struktury i Geologicheskoi Istorii SSSR* (Brief Outline of Geological Structure and Geological History of the USSR), Moscow: Akad. Nauk SSSR, 1937.

Arkhipov, I.V. and Schatsky, N.S., Conception of "Facies," *Izv. Vyssh. Uchebn. Zaved., Geol. Razved.*, 1985, no. 10, pp. 78 - 82.

Cherskii, I.D., Geology of the Interior Asia, *Tr. Sanktpeterburgsk. O-va Estestvoisp.*, 1886, vol. 17, no. 2.

Keller, B.M., *Flishevaya Formatsiya Paleozoya v Zilairskom Sinklinorii na Yuzhnom Urale i Skhodnye s Nei Obrazovaniya* (Paleozoic Flysch Formation in the Zalair Synclinorium of the Southern Urals and Similar Formations), Moscow: Akad. Nauk SSSR, 1949.

Keller, B.M. and Schatsky, N.S., Problems of the Upper Precambrian Geology, *Zhizn' i Tvorchestvo Akademikov A.D. Arkhangel'skogo i N.S. Shatskogo. Ocherki po Istorii Geologicheskikh Znanii* (Life and Creative Genuis of Academicians A.D. Arkhangel'skii and N.S. Schatsky: Essays on the History of Geological Knowledge), Moscow: Nauka, 1973, issue 16, pp. 156 - 168.

Khvorova, I.V., *Flishevaya i Nizhnemolassovaya Formatsiya Yuzhnogo Urala* (Flysch and Lower Molassic Formation of the South Urals), Moscow: Akad. Nauk SSSR, 1961.

Kosygin, Yu.A., *Opyt Intellektual'noi Avtobiografii* (Autobiography of Creative Activity), Vladivostok: Dal'nauka, 1993.

Lapkin, I.Yu., Discovery of the East Ukrainian Oil-Gas Field by the Comparative Tectonics Method, *Zhizn' i Tvorchestvo Akademikov A.D. Arkhangel'skogo i N.S. Shatskogo. Ocherki po Istorii Geologicheskikh Znanii* (Life and Creative Genius of Academicians A.D. Arkhangel'skii and N.S. Schatsky. Essays on the History of Geological Knowledge), Moscow: Nauka, 1973, issue 16, pp. 170 - 175.

Menner, V.V. and Schatsky, N.S., Paleogene Stratigraphy in the Eastern Caucasus, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1927, vol. 5, no. 1, pp. 39 - 60.

Obruchev, V.A., *Geologicheskii Obzor Sibiri* (Geological Review of Siberia), Moscow: Gosizdat, 1927.

Pavlov, A.P., Changes in Geography of Russia during the Jurassic and Cretaceous Time, *Nauchn. Slovo*, 1903, vol. 2, pp. 143 - 145.

Ryabukhin, G.E., Nikolai Sergeevich Schatsky in Eastern Siberia, *Zhizn' i Tvorchestvo Akademikov A.D. Arkhangel'skogo i N.S. Shatskogo. Ocherki po Istorii Geologicheskikh Znanii* (Life and Creative Genius of Academicians A.D. Arkhangel'skii and N.S. Schatsky: Essays on the History of Geological Knowledge), Moscow: Nauka, 1973, issue 16, pp. 141 - 155.

Shantser, E.V., Scientific Activities of N.S. Schatsky at the Moscow Geological Prospecting Institute, *Izv. Vyssh. Uchebn. Zaved., Geol. Razved.*, 1985, no. 10, pp. 108 - 109.

Schatsky, N.S., Tectonics of the Northern Donets Basin, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1923 - 1924, vol. 2, no. 3, pp. 257 - 278.

Schatsky, N.S., Stratigraphy and Tectonics of Upper Cretaceous and Lower Tertiary Deposits at the Northern Border of the Donets Ridge. (Report on the Work in 1922), *Tr. Osoboi Komissii po Issledovaniyu Kurskikh Magnitnykh Anomalii pri Prezidiume VSNKH* (Proc. of Special Commission of the Presidium of the Highest Council of People Economy on Research of the Kursk Magnetic Anomalies), Moscow, 1924, issue 5, pp. 82 - 152.

Schatsky, N.S., Notes on the Tectonics of Tertiary Piedmonts of the Northeastern Caucasus. *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1927, vol. 5, nos. 3 - 4, pp. 321 - 369.

Schatsky, N.S., Facies and Oil Occurrence in the Maikop Deposits of the Southeastern Caucasus, *Neft. Khoz.*, 1928, vol. 15, no. 8, pp. 160 - 172.

Schatsky, N.S., Geological Structure of the Eastern Part of the Chernye Gory and the Miatly and Dylym Oil Deposits (Northern Daghestan), *Tr. Gos. Issled. Neft. Inst.*, Moscow: VSNKH. Nauch. Tekhn. Upr., 1929, no. 4.

Schatsky, N.S., Origin of the Romny Gypsum and Rocks of the Isachkov Mountain in the Ukraine, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1931, vol. 9, nos. 3 - 4, pp. 336 - 349.

Schatsky, N.S., Main Tectonic Features of the Siberian Platform, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1932, vol. 10, nos. 3 - 4, pp. 476 - 509.

Schatsky, N.S., Tectonics of the Arctic, *Geologiya i Poleznye Iskopaemye Severa SSSR. Trudy I Geologo-Razvedochnoi Konferentsii Glavsevmorputi 24 - 27 Aprelya 1935 Goda* (Geology and Mineral Deposits of the Northern USSR. Proc. of the I Geol. Prosp. Conf. of Glavsevmorput', April 24 - 27, 1935), 1935, vol. 1, pp. 149 - 145.

Schatsky, N.S., Ch. Darwin's Geological Observations, *Ch. Darvin, Soch., T. 2* (Ch. Darwin, Works, Vol. 2), Moscow: Biomedgiz, 1936a, pp. 451 - 462.

Schatsky, N.S., Darwin as a Geologist, *Ch. Darvin, Soch., T. 2* (Ch. Darvin, Works, Vol. 2), Moscow: Biomedgiz, 1936b, pp. 241 - 273.

Schatsky, N.S., Monograph on Cirripedia Fossils, *Ch. Darvin, Soch. T. 2* (Ch. Darwin, Works, Vol. 2) Moscow: Biomedgiz, 1936c, pp. 43 - 44.

Schatsky, N.S., On Neocatastrophism (with Regard to Orogenic Phases and Folding Nature), *Probl. Sov. Geol.*, 1937a, vol. 7, no. 7, pp. 532 - 551.

Schatsky, N.S., On Tectonics of the East European Platform, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1937b, vol. 15, no. 1, pp. 4 - 27.

Schatsky, N.S., Origin of the Donets Basin, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1937c, vol. 15, no. 4, pp. 326 - 347.

Schatsky, N.S., Twenty Years of Soviet Geotectonics, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1937d, vol.15, no. 5, pp. 385 - 391.

Schatsky, N.S., Tectonics of Central Kazakhstan, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1938, nos. 5 - 6, pp. 737 - 767.

Schatsky, N.S., Movements and Evolution of the Earth's Crust, *Sov. Geol.*, 1939a, vol. 9, no. 8, pp. 3 - 6.

Schatsky, N.S., Orogenic Phases and Folding, *Tr. XVII Sessii Mezhdunarodnogo Geologicheskogo Kongressa, 1937* (Proc. XVII Sess. of Int. Geol. Cong., 1937), Moscow: Akad. Nauk SSSR, 1939b, vol. 2., pp. 323 - 330.

Schatsky, N.S., Age of the Folded Basement of the Russian Platform, *Sov. Geol.*, 1940a, vol. 10, no. 10, pp. 5 - 10.

Schatsky, N.S., Syneclises as Interpreted by A.P. Pavlov, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1940b, vol. 18, nos. 3 - 4, pp. 39 - 52.

Schatsky, N.S., *Roderik Impi Murchison (1792 - 1871)* [Roderick Impey Murchison (1792 - 1871)], Moscow: Mosk. O-vo Ispyt. Prir., 1941.

Schatsky, N.S., Solid Bitumen Deposits (Asphalt, Asphaltite, Pyrobitumen) and the Geological Conditions of Their Formation), *Nemetallicheskie Iskopaemye SSSR, T. 2, Bazal't-Boksit* (Nonmetallic Deposits of the USSR, Vol. 2, Basalt-Bauxite), Moscow: Akad. Nauk SSSR, 1943, pp. 212 - 246.

Schatsky, N.S., *Andrei Dmitrievich Arkhangel'skii (1879 - 1940)* [Andrei Dmitrievich Arkhangel'skii (1879 -1940)], Moscow: Mosk. O-vo Ispyt. Prir., 1944.

Schatsky, N.S., Comparative Tectonics of North America and Eastern Europe, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1945a, no. 4, pp. 10 - 26.

Schatsky, N.S., Development of Geology and Geological Research at the Academy of Sciences, *Ocherki po Istorii Akademii Nauk. Geologo-Geograficheskie Nauki* (Essays on the History of the Academy of Sciences. Geologo-Geographical Sciences): Moscow: Akad. Nauk SSSR, 1945b, pp. 9 - 32.

Schatsky, N.S., Essays on Tectonics of the Volga-Urals Oil Bearing Province and Adjacent Western Slope of the Southern Urals, *Materialy k Poznaniyu Geologicheskogo Stroeniya SSSR* (Materials on the Geological Structure of the USSR), Moscow: Mosk. O-vo Ispyt. Prir., 1945c.

Schatsky, N.S., Chudakov, E.A., and Lupinovich, I.S., Oil Resources of the Second Baku, *Osnovnye Itogi Rabot za 1942 - 1944 gg. Komissii po Mobilizatsii Resursov Srednego Povolzh'ya i Prikam'ya SOPSa AN SSSR* (Main Results of Works in 1942 - 1944 of Commission of the USSR Academy of Sciences on Mobilizatition of Resources of the Middle Volga-Kama Region), Moscow: Akad. Nauk SSSR, 1945d, pp. 70 - 81.

Schatsky, N.S., Comparative Tectonics of Ancient Platforms: 1. Main Features of the Structure and Evolution of the East European Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1946a, no. 1, pp. 5 - 62.

Schatsky, N.S., Comparative Tectonics of Ancient Platforms: 2. Bol'shoi Donbass and the Vichita System, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1946b, no. 6, pp. 57 - 90.

Schatsky, N.S., Structural Relations of Platforms with Folded Geosynclinal Regions, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1947a, no. 5, pp. 37 - 56.

Schatsky, N.S., Works by A.P. Karpinskii on Tectonics of the East European (Russian) Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1947b, no. 1, pp. 33 - 50.

Schatsky, N.S., A.P. Karpinskii as Scientist (on His 100th Birthday), *Sov. Geol.*, 1948a, no. 28, pp. 3 - 15.

Schatsky, N.S., Deep Dislocations Affecting Platforms and Foldbelts (the Volga Region and Caucasus), *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1948b, no. 5, pp. 39 - 66.

Schatsky, N.S., Vladimir Aphanas'evich Obruchev (on His 85th Birthday), *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1948c, no. 5, pp. 5 - 10.

Schatsky, N.S., A Manual of Soviet Geologists, Obruchev V.A.: History of Geological Exploration of Siberia. Issues 1 - 9. 1931 - 1949, *Novyi Mir*, 1950, no. 5, pp. 265 - 266.

Schatsky, N.S., Duration of Fold Formation and Folding Phases, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1951, no. 1, pp. 15 - 53.

Schatsky, N.S., Ancient Deposits in the Sedimentary Cover of the Russian Platform and Its Structure in the Older Paleozoic, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952a, no. 1, pp. 17 - 32.

Schatsky, N.S., The Paleozoic-Proterozoic Boundary and the Riphean Deposits of the Russian Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952b, no. 5, pp. 36 - 49.

Schatsky, N.S., Alexandr Petrovich Karpinskii, *Bol'shaya Sovetskaya Entsiklopediya* (The Greater Soviet Encyclopedia), Moscow: Gosnauchizd., 1953a, 2nd ed., vol. 20, pp. 248 - 250.

Schatsky, N.S., Charles Lyell (1797 - 1875), *Bol'shaya Sovetskaya Entsiklopediya* (The Greater Soviet Encyclopedia), Moscow: Gosnauchizd., 1953b, 2nd ed., vol. 24, pp. 320 - 331.

Schatsky, N.S., Manganese-Bearing Formations and Manganese Metallogeny, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1954, no. 4, pp. 3 - 37.

Schatsky, N.S., Comparative Tectonics of Ancient Platforms: 5. The Pachelm Trough Origin, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1955a, vol. 30, no. 5, pp. 5 - 26.

Schatsky, N.S., Geological Sciences in the Moscow Society of Naturalists (On the 150th Anniversary of Mosk. O-vo Ispyt. Prir.), *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1955b, vol. 30, no. 5. pp. 125 - 137.

Schatsky, N.S., Phosphoritic Formations and Classification of Phosphorite Deposits, *Tr. Soveshchaniya po Osadochnym Porodam* (Proc. of Conference on Sedimentary Rocks), Moscow: Akad. Nauk SSSR, 1955c, pp. 6 - 100.

Schatsky, N.S., Gressly Amanz (1814 - 1865), *Bibliograficheskii Slovar' Deyatelei Estestvoznaniya i Tekhniki* (Biographical Glossary of Prominent Figures of Natural Sciences and Technics), Moscow, 1958a, vol. 1, pp. 262 - 263.

Schatsky, N.S., Gressly Amanz (1814 - 1865), *Bol'shaya Sovetskaya Entsiklopediya* (The Greater Soviet Encyclopedia), Moscow: Gosnauchizd., 1958b, 2nd ed., vol. 51, pp. 87 - 88.

Schatsky, N.S., Karpinskii Alexandr Petrovich, *Biograficheskii Slovar' Deyatelei Estestvoznaniya i Tekhniki* (Biographical Glossary of Prominent Figures in Natural Sciences and Technics), Moscow, 1958c, vol. 1, pp. 399 - 401.

Schatsky, N.S., Lyell Charles (1797 - 1875), *Biograficheskii Slovar' Deyatelei Estestvoznaniya i Tekhniki* (Biographical Glossary of Prominent Figures in Natural Sciences and Technics), Moscow, 1958d, vol. 1, pp. 485 - 486.

Schatsky, N.S., Main Directions in Research on the Problem: "Regularities in Distribution of Mineral Deposits in Earth Crust as a Basis for Their Search in the USSR Territory," *Zakonomernosti Razmeshcheniya Poleznykh Iskopaemykh, T. 1* (Regularities in Distribution of Mineral Deposits, Vol. 1), Moscow: Akad. Nauk SSSR, 1958, pp. 3 - 32.

Schatsky, N.S., Scientific Works of M.S. Shvetsov, *Tr. Mosk. Geol.-Razved. Inst.*, Moscow, 1958f, pp. 5 - 8.

Schatsky, N.S., Geotectonic Regularities in Distribution of Endogenic Ore Deposits, *Izv. Vyssh. Uchebn. Zaved., Geol. Razved.*, 1960a, no. 11, pp. 9 - 18.

Schatsky, N.S., Parageneses of Sedimentary and Volcanogenic Rocks and Formations, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1960b, no. 5, pp. 3 - 23.

Schatsky, N.S., Principles of Late Precambrian Stratigraphy and Stratigraphic Range of the Riphean Group, *Stratigrafiya Pozdnego Dokembriya i Kembriya* (Late Precambrian and Cambrian Stratigraphy), Moscow: Akad. Nauk SSSR, 1960c, pp. 5 - 15.

Schatsky, N.S., Facies and Formations (Gressly and His Concept on Facies), *Izbr. Tr., T. 4* (Selected Works: Vol. 4), Moscow: Nauka, 1965, pp. 219 - 232.

Schatsky, N.S., Role of Academician A.A. Borisyak in Development of Russian Geology, *Uchenye Geologicheskogo Komiteta* (*Ocherki po Istorii Geologicheskikh Znanii. Vyp. 13*) [Scientists of the Geological Committee. (Essays on History of Geological Knowledge. Issue 13)], Moscow: Nauka, 1971, pp. 8 - 17.

Schatsky, N.S. and Bogdanov, A.A., International Tectonic Map of Europe, Scale 1: 2 500 000, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1961, no. 4, pp. 3 - 24.

Schatsky, N.S., Troughs of the Donets Type, *Izbr. Tr., T. 2* (Selected Works: Vol. 2), Moscow: Nauka, 1964, pp. 544 - 553.

Schatsky, N.S. and Davydova, T.N., The Mesozoic in the Northern Part of the Bureya Coal Field: Part 2, *Tr. Vses. Nauchno-Issl. Inst. Miner. Syr'ya,* 1937, no. 123a, pp. 3 - 46.

Schatsky, N.S. and Khokhryakova, V.A., Possibility of Applying Opokas and Tripolis as Adsorbents in the Oil-Refining Industry, *Neft. Khoz.*, 1926, vol. 2, no. 8, pp. 228 - 232.

Schatsky, N.S. and Pavlovskii, E.V., Academician Vladimir Afanas'evich Obruchev (1863 - 1956), *Razved. Okhr. Nedr,* 1956, no. 8, pp. 61 - 63.

Schatsky, N.S., *et al.*, *Zakonomernosti Razmeshcheniya Glavneishikh Poleznykh Iskopaemykh v Zemnoi Kore kak Osnova dlya Ikh Prognoza na Territorii SSSR* (Regularities in Distribution of Major Mineral Resources in the Earth's Crust as a Basis for Their Prognosis in the Territory of the USSR), Moscow: Akad. Nauk SSSR, 1954.

Sokolov, B.S., *Vendskaya Sistema. Istoriko-Geologicheskoe i Paleontologicheskoe Obosnovanie* (Vendian System: Its History, Geology, and Paleontology), Moscow: Nauka, 1985, vols. 1, 2.

Starostina, Z.M., *Sideritovaya Formatsiya Rifeya Zapadnogo Sklona Yuzhnogo Urala* (Riphean Siderite-Bearing Formation at the Western Slope of the Southern Urals), Moscow: Akad. Nauk SSSR, 1962.

Tektonicheskaya Karta SSSR dlya Vysshikh Uchebnykh Zavedenii, Masshtab 1 : 4 000 000 (Tectonic Map of the USSR For Higher School, Scale: 1 : 4 000 000), Schatsky, N.S., Ed.-in-Chief, Moscow: Gos. Upr. Geol. Kart, 1953.

Tektonicheskaya Karta SSSR i Sopredel'nykh Stran, Masshtab 1 : 5 000 000 (Tectonic Map of the USSR and Adjacent Countries, Scale: 1 : 5 000 000), Schatsky, N.S., Ed.-in-Chief, Moscow: Gosgeoltekhizdat, 1956.

Tikhomirov, V.V., Geological History and Philosophy in Schatsky's Works, *Ocherki po Istorii Geologicheskikh Znanii, Vyp. 10* (Essays on History of Geological Knowledge, Issue 10), Moscow: Akad. Nauk SSSR, 1962, pp. 90 - 110.

Usov, M.A., *Fazy i Tsikly Tektogeneza Zapadno-Sibirskogo Kraya* (Phases and Cycles of Tectonogenesis in Western Siberia), Tomsk: Zap.-Sib. Geol. Trest, 1936.

Usov, M.A., Phases of Tectogenesis, *Sov. Geol.*, 1938, vol. 8, no. 11, pp. 9 - 21.

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The Studies on Platforms by N. S. Schatsky and Modern Approaches

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Abstract – Different directions were created and considered in N.S. Schatsky's investigations of platforms: regional tectonics; structural elements of platforms; comparative tectonic analysis; inheritance phenomena in the basement-cover system; transverse marginal elements and aulacogens; studies on geological formations; tectonic cycles; critiques of neocatastrophism and mobilism. As a result of a brief analysis, from the standpoint and possibilities of modern geology, a list of recent priority directions in platform studies is proposed to show how they differ from those priorities of Schatsky's lifetime.

Key words: *Tectonics, intraplate tectonics, platforms, basement, cover, aulacogens, geological formations, rifting, sedimentary basins*

During the thirty years after Schatsky's death, tectonics, as well as geology as a whole, have greatly progressed. In fact, some features of the geology of the 1940 - 1950s, the days of Schatsky's greatest creative successes, may now seem somewhat naive. First, let us recall the general geology standard and the degree of regional investigations of those years. Deep-drilling on platforms was in its early stages. While it brought forth sensational discoveries, the data collected were fragmented. The northeastern regions of the country were virtually a blank space on geological maps, while many other regions in Soviet Asia were poorly studied. Almost nothing was known about shelves or the ocean floor. Only a great talent was able to create long living conceptions on the basis of existing material.

It was during those years, however, that modern tectonics was founded. It is no exaggeration to contend that this was related, first of all, to Schatsky's studies, especially in elaborating principal aspects of the tectonic theory of platforms or even, in a broader respect, of the doctrine of platform tectonics. Schatsky is the founder of many concepts that form the basis of modern ideas and continue to improve even at the present time. His role in the formation of the tectonic school in our country is analogous to that of his contemporary H. Stille, another pioneer in tectonics. (At the same time, they were scientists of a different mentality, and Stille's views were criticized strongly by Schatsky.)

This paper regards the principal directions of the investigations by Schatsky of the tectonics of platforms, which are united in the following groups: (1) regional tectonics of platforms, (2) structural elements of platforms, (3) comparative tectonic analysis, (4) inheritance phenomena in the basement-cover system, (5) transverse marginal elements, and aulacogens, (6) geological formations, (7) tectonic cycles and criticism of neocatastrophism critics, and (8) analysis of mobilism.

An attempt at reexaming the problems developed by Schatsky from the perspective of modern geology is presented here, but a rendering of his scientific heritage is not. For the later purpose, it is simple to refer to his own works. In addition to demonstrating the rates of scientific development, such a view allows me to emphasize the current directions in the study of platforms, separating them from those which have exhausted themselves as subjects for sound theoretical interests.

In the list mentioned above, tectonic maps, an important area of Schatsky's work, are consciously not included, as they deserve a separate analysis.

REGIONAL TECTONICS OF PLATFORMS

Strictly regional problems are not analyzed here. However, to understand the roots of Schatsky's special interest in certain aspects of platform tectonics, the structure and the role of transverse marginal elements and aulacogens, as well as the classification of platform elements, it should be taken into account that the ancient East European and North American platforms were his favorite platforms. He composed a set of regional compilations on the former (Schatsky, 1937a, 1937b, 1940, 1945b, 1946a), and both of them served as a permanent source of material for improving the terminology concerning platform elements and for theoretical generalizations on comparative analysis (Schatsky, 1945a, 1946c, and others).

Schatsky occasionally turned to other platforms, mainly, for the purpose of confirming his conclusions based on the materials from the two aforementioned platforms. Already in 1932, he published the work

"Principal Tectonic Features of the Siberian Platform" (Schatsky, 1932), that was a generalization, the first one after V.A. Obruchev's works, of still fragmentary data on the Siberian platform. Despite the exclusive attention he gave to ancient platforms, after that time, Schatsky did not return to the Siberian platform, except for his work on tectonic maps.

The epi-Paleozoic platforms, specifically in Western Siberia and Kazakhstan, were in Schatsky's circle of interests, mainly as subjects for his study on the problem of inherited tectonic features of basements in the cover elements.

STRUCTURAL ELEMENTS OF PLATFORMS

Schatsky considered the problems of terminology, definition, and classification of ancient platform elements. He outlined a hierarchical system of concepts regulating terminology (Schatsky, 1945b, 1947), that is used with variations and additions even now.

Naturally, of principal interest are not the terminologic nuances, but his ideas on the features of the tectonic regime and on the role of principal groups of elements in platform tectonics, namely, of the high-rank elements, such as shields and plates, or, anteclises and syneclises.

Schatsky emphasized that there is a principal difference between shields and anteclises. In his opinion, shields are independent tectonic forms of ancient platforms (cratons), and not simply crowns of uplifts like anteclises; they show a steady, though not necessary continuous, uprise within fixed limits, i.e., the regularity of outlines. According to Schatsky, the total shield erosion was insignificant at the platform stage despite the steady rising trend, and could be approximated by a magnitude of a few kilometers; only some shields were exceptions (he noted the Anabar shield and the Llano uplift on the North American platform), where the thickness of rocks removed by erosion was estimated to be several kilometers.

Little was known on the tectonic regime of shields at the platform stage during Schatsky's time. It is understandable, as there were no methods for deciphering the rock records in regions of permanent uprise of a vast area, when it is difficult to successfully extrapolate and interpolate sections along their periphery. This is a problem even now, though some research (e.g., on the Baltic shield; Garbar *et al.*, 1991) provides evidence that shields (or some of them?) are elements, which are not only steadily uprising, but also tectonically more active in other respects than was commonly thought, i.e., the elements with a relatively complex geological history. Evidently, one can anticipate a solution of the problem of tectonic regime, history and erosion depth of shields in the near future by means of developing different, thermobathymetric, isotope-geochemical, and crystallochemical methods of reconstructing the P–T-trajectories for rocks and minerals, including those of low-temperature metamorphism. More and more such works appear in recent literature, although they concern mostly uplifts within mobile belts rather than the shields. The problem of the geodynamics of ancient platform shields, unknown in this respect in Schatsky's time, has acquired significance nowadays. It may be formulated, perhaps, as follows: how much of a shield crust (lithosphere) is tectonically active; and if active, would the activity be an integral, immanent property of the shields, or would it not be displayed in all cases, but only under certain forms of shield tectonic activation (when they come across a sphere of activity of a hot spot (plum?) or, for instance, are affected from the side of neighboring mobile belts, as it may be suggested, with great caution, for the system of the Baltic shield-Scandinavian Caledonides of the Riphean-early Paleozoic)? The understanding of shield geodynamics, as well as their subdivision into different types according to the tectonic regime, depend on the answer to this question. It is not inconceivable, that some of them (Anabar shield?) would be close to anteclises in these features.

As for anteclises and syneclises, in Schatsky's opinion, the active role belongs to syneclises, and the anteclises are remnant elements. This conclusion, based dominantly on the outline of both plain view and general intuition does not require revision. Geological data (drilling), features of the crust structure (namely the crustal structure revealed by seismic reflection profiles), as well as diverse model reconstructions indicate the activity of tectonic processes to be concentrated in syneclises, or sedimentary basins, as they are more often called now. In this sense, syneclises, especially deep ones, are perhaps analogues of tectonically active shields, but with an opposite direction of movement. The anteclises, being the crustal areas with a low amplitude of vertical displacements, may actually be considered as relatively neutral elements.

It is pertinent to note here one more category of platform elements, the detached covers. While it clear now that they exist, they received Schatsky's skeptical consideration, the Jura Mountains as an example, though he did not deny disharmonious phenomena, including those in the Jura cover, provided that covering deposits separated by a disharmony horizon (in the Jura Mts. by Triassic salt-bearing horizon) remain, in principle, in the original position (Schatsky, 1950). Here, we can see the negative reaction of Schatsky to tectonic nappes in general; he doubted their reality even in such classical areas of nappe tectonics as the Alps and the Appalachians (Schatsky, 1954).

COMPARATIVE TECTONIC ANALYSIS

Comparative analysis is a method applicable in all natural sciences, dealing with natural phenomena. In tectonics, it was in use even before Schatsky. He, himself, listed his forerunners: M. Bertrand, E. Suess, V. van der Gracht, H. Stille, A.B. Bailey, P. Furmarier,

D.N. Sobolev, A.D. Arkhangel'skii, and possibly others. However, it is possible to say, with good reason, that it was Schatsky who introduced comparative analysis to tectonics as a clearly formulated method. After his work, comparative analysis turned into a reliable and consciously applicable tool for tectonic investigations. Schatsky explained the advantages of the comparative method with the following statement: "A geologist is ... like ... a biologist discovering by the comparative method such features ... of organisms that slipped out his view during the usual descriptive systematics" (Schatsky, 1947).

Consistent application of the comparative method allowed Schatsky to make, for instance, such significant generalizations as the elucidation of common regularities in the evolution of ancient platforms based on the comparison of the East European and North American platforms, and to develop ideas on transverse and marginal elements such as the Great Donbass and Wichita and, later, the idea on aulacogens. Comparative analysis was an important component in the studies on geological formations performed by Kheraskov and Schatsky, and in the elaboration of the principles of compiling the tectonic maps.

An example of a concrete application of the method was the conclusion made in 1940, prior to drilling, suggesting the presence of the Upper Precambrian rocks at the base of the Russian platform cover in the Serpukhov area (Schatsky, 1940). A number of authors interpreted very thick sediments (4 - 4.5 km) discovered here as the Lower Paleozoic, whereas Schatsky suggested the presence here of "the Upper Precambrian nonmetamorphic geological formations confined to large grabens" (Schatsky, 1940, p. 283) based on two premises: (a) the known trends in the East European platform development, which made the presence of thick Lower Paleozoic sediments in its central part scarcely probable, and (b) analogies with the Precambrian of India.

Soon, comparative analysis became an effective tool for investigating in the tectonic school of the USSR. It brought about the success of many significant generalizations, among them the works elucidating developmental phases and other regularities in the evolution of mobile (fold) belts and of the continental crust formation, as well as the subsequent compilation of tectonic maps from Schatsky's first Tectonic Map of the USSR and Neighboring Countries (*Tektonicheskaya Karta* ..., 1956) up to the Tectonic Map of Northern Eurasia (Peive *et al.*, 1976). Perhaps, it would be unnecessary to recall the history if it wasn't for the fact that, in recent years, the interest in generalizations on the basis of comparative analysis decreased in geotectonics, specifically, in the studies on platform tectonics. Meanwhile, the available material on the sedimentary cover structure, basement and crust of all continental platforms allows us to introduce essential corrections to existing ideas on the regularities of platform and intraplate tectogenesis, which can be done only on the basis of comparative investigation, thus revealing the vital connections between different features and phenomena.

INHERITANCE PHENOMENA IN THE BASEMENT-COVER SYSTEM

Concerning the problem of inheritance, Schatsky emphasized the difference between ancient and young platforms (Schatsky, 1947, 1951). Its essence is as follows. On ancient platforms, tectonic elements of the sedimentary cover, for the most part ("in an overwhelming majority of cases"), are not related to the elements of the crystalline basement, in other words, the inheritance of elements is absent (besides the inherited development of elements *within* the cover itself, which is a common and even typical phenomenon according to Schatsky; for instance, the position of the pre-Devonian Pachelma depression is later inherited by a syneclise of a similar strike, etc.). On the contrary, a distinct structural inheritance characterizes young platforms, for instance in western Siberia and central Kazakhstan, where it is evident from the strike and localization of positive and negative elements. In addition, these posthumous dislocations are expressed especially brightly at the lower structural stage of the epi-Paleozoic sedimentary cover (in the Triassic-Middle Jurassic deposits). Distinguishing this stage, Schatsky created a prototype of transitional complexes of young platforms, the idea further developed in works by N.A. Krylov and others.

Schatsky's ideas on the difference between ancient and young platforms in degree of development of inheritance phenomena are correct to a certain extent, and have to be considered as a first approximation only. In general, they need revision. The ancient platform basement, undoubtedly, is not so homogenous and passive as was believed earlier, when data on the basement structure were scarce even for shields, and the concealed areas were, in this respect, blank spaces in general. Present data show that the general structural plan of the East European platform is highly dependent on the basement structure. Without going into detail, I have to note that such relations are best evident from the concordance between platform paleorifts (aulacogens), large tectonic sutures and Proterozoic mobile belts recognizable in the crystalline basement structure (e.g., Dedeev *et al.*, 1973). The fact that the basement elements did not lose their ability to the reactivation, and that the basement, on the whole, was not transformed into a homogenous isotropic mass, is proved by observations on neotectonics and recent activity of the Early Precambrian elements in Karelia (Zykov, 1991; and M.G. Leonov, personal communication). These and similar phenomena may be explained in two ways: first, as an activation (reactivation) of the structural framework in the present stress field and, second, as deformations in response to the release of internal energy within the structurally and compositionally heterogeneous

substratum under the external forces of different kinds (stress pattern change, P-T-condition variations, and other; Genshaft, 1995).

At any rate, the problem of deformation and other processes within the basement of ancient platforms (cratons) and of their reflection in the cover is quite significant at the present stage of platform study. I think, that as the materials accumulate, the traditional thesis on the sclerotics of ancient platform basements will increasingly lose its literal sense.

TRANSVERSE MARGINAL ELEMENTS. AULACOGENS

The theme of transverse marginal elements and troughs on platforms was one of the principal themes in Schatsky's works (Schatsky, 1945a, 1946c, 1955a). As a result, its development in 1960 led to the aulacogen conception (Schatsky, 1964), which added a very new and important direction to platform study. In spite of the morphological diversity of transverse elements, they, according to Schatsky, are characterized by the following common features: all are confined to the reentrant corner of platforms, comprise the platform geological formations, and show undoubted affiliation to platform elements. Schatsky, for instance, emphasized that Donbass is an intracratonic zone and not the Variscan geosyncline wedged out westward. He believed, that the discovery of troughs (aulacogens) on the Russian platform (Pachelma, Krestsy, Kazan-Sergeev), in addition to the already known Donbass, was one of the most significant geological discoveries in the USSR in those years. He also suggested, with good reason, that these elements and their analogues, distinguishable in other platforms, should be regarded as "principal elements of plates, and may be among the principal elements of the earth crust in gross since the Riphean time" (Schatsky, 1964).

The present theme is fully illuminated in literature, and, as such, will not be repeated here. However, it is of interest to consider one of its aspects.

Schatsky distinguished two principal groups of aulacogens, composing the framework, in his opinion, for any further, more elaborated classification: (a) simple (Pachelma, Krestsy, etc.), (b) compound (Great Donbass, Wichita, Holy Cross Mountains). A distinctive feature of compound aulacogens is the combination of their constituent elements: depressions, uplifts and, of particular significance, fold systems. From the point of view of element morphology, such a subdivision is not problematic. It is unclear, however, as to what extent these two groups of aulacogens may be considered as originally opposite genetic types of structures. Are the differences between them, specifically the deformations in the compound aulacogens, of a determinant origin, as one would say nowadays? Or do they represent the superimposed phenomenon, unrelated to the nature (initial process of origin) of aulacogens?

Schatsky noted the presence of fold systems within compound aulacogens as a characteristic feature of the latter, but he did not speculate on the factors responsible for their origin. At present, it seems more natural to correlate the deformation of sedimentary rocks in aulacogens with changeable geodynamic conditions within the respective part of a platform or lithosphere plate, namely, with the alternation of extension (during the epoch of rift development) and compression or transpression regimes (during the epoch of deformation), than with the initially determined features of their structure. The restriction of intraplate deformations to aulacogens as to the zones of already existing displacements in the crust is understandable. In addition, deformations are vivid here because of the presence of thick sedimentary rocks filling aulacogens, which form after deformations and inversion of the morphologically expressed fold structure. During such episodes of compression, fracture systems of the rift stage may be activated, but now with opposite kinematics, with upthrows instead of downthrows. It is likely that the development of many structures fitting into this category of compound aulacogens occurred in the East European and other platforms, in this very manner. Otherwise, when the rift (aulacogen) does not suffer from compression (transpression) and deformations, the crust and sedimentary basin within it are left undeformed (noninversed), and the aulacogen comes to be or, more accurately, remains in the simple aulacogens category. Thus, the subdivision of aulacogens into simple and compound types most likely reflects an integral final result depending on the geodynamic history of a platform.

It should be explained how the correspondence of terms, aulacogen and rift, is interpreted here. They are regarded as synonyms in terms of the mechanism and geodynamic conditions of their formation. Moreover, their configuration, size, and age are not very significant. The difference between them, assuming a separate use of the terms, follows from their position in the present structure of the earth crust: the rift is the structure open to the surface and uncovered by sediments, while the aulacogen is the totally concealed, platform rift conserved in the structure of the sedimentary cover. In addition, aulacogens affect the development of platform structure and the formation of the sedimentary cover for a long time. For instance, the well known regularity in the formation of platform depressions and syneclises over aulacogens (rifts) is such a consequence, though this appears to be attributable only to certain relatively large aulacogens.

FORMATIONAL METHOD (THEORY OF GEOLOGICAL FORMATIONS)

Schatsky and Kheraskov (1967), together with a number of other scientists, are among the founders of the formational method, or the theory of geological formations, which considerably affected investigations in

the field of geotectonics, lithology, and metallogeny. His works, where the essence and principal goals of this method are formulated, as well as works on phosphorite- and manganese-bearing geological formations, are well-known (Schatsky, 1955b, 1960, 1965a, 1965b, 1965c). An enormous series of publications is devoted to geological formations, including the polemics on different aspects of this theory. The principal achievement of the formational method in geotectonics seems to be the recognition of the vertical and horizontal series of geological formations that afford the ability to foster a better understanding of regularities in crustal development. In other words, the method creates models of the principal tectonic elements and elucidates the general trend in the earth's crustal evolution.

Below, I focus attention on Schatsky's view on two problems directly related to platform tectonics and to geological formation of the platform type: (a) the correlation of platform and geosynclinal geological formations and (b) primary and secondary formations of the platform type. It seems reasonable to touch upon the general ideas on the distinction between platforms and geosynclines in connection with the first problem, as well.

Schatsky was very categorical in dividing geological formations into geosynclinal and platform types [Although, it is possible to find in his works some remarks, which seem somewhat contradictory to such an explicit subdivision. For instance, in the paper "Regularities of the Occurrence of Ore Deposits in Platform Regions" (Schatsky, 1965b, p. 185), it is noted, that "many types of platform deposits are confined not only to platform regions, but also to geosynclinal belts," because, he explained, of the presence of geological formations of a platform type in geosynclinal fold regions].

His approach was in an agreement with the ideas accepted by a majority of researches, the adherents of the geosynclinal theory, where geosynclinal belts were identified as deformation belts ("geosynclinal folding"), i.e., the principle of determinate development (according to which, the geosynclinal development led inescapably to a final folding) was the basic one, and the belts were distinguished exactly by the presence of fold structures. In addition, this theory suggested an almost mystic contrast between platforms and geosynclines, between the platform and geosynclinal types of movements, and, of course, between platform and geosynclinal geological formations. Correspondingly, very significant efforts of that time were aimed to discriminate the platform and geosynclinal areas; a good illustration is a long and, as it seems to me, groundless discussion on the tectonic nature and boundaries of the Donbass (in terms of the geosyncline-platform alternative). Schatsky saw the task of the Donbass tectonics, "first of all, in elucidating the natural tectonic boundaries of this structure" (Schatsky, 1946c), meaning exactly the place of transition from geosyncline to platform.

It is now known that a much wider range of tectonic units forms the structure of fold belts in addition to tectonic elements and geological formations of the geosynclinal type (in past terminology). Such units are represented by relics of the oceanic crust, by fragments of the platform crust in a form of terranes, and by marginal platform areas affected by deformations. The latter gave rise to the concept of the deformation front which generally does not coincide with the mobile belt boundary. The determination principle, in the straight sense, seems to be discredited now. The deformation stage is not predetermined by history (the "geosynclinal downwarping"), but rather, depends on changeable geodynamic conditions. Any area of the earth crust may undergo a deformation under forces of a proper magnitude. The deterministic principle is valid only when it concerns the dependence of the deformation style on mechanical properties of the crust, including the properties of rocks accumulated before the epoch of deformation.

Therefore, nowadays, the distinction of platforms and geosynclines and, correspondingly, the platform and geosynclinal geological formations requires a more correct approach (especially because of the radically changed attitude toward this concept). Certainly, the subdivision of geological formations into these two groups appears to be impossible. Similar geological formations, especially if they are discriminated severely, can occur on and off platforms.

In several works, Schatsky regarded the regularities of accumulation and formational affinity of platform ore deposits (Schatsky, 1955a, 1965b, 1965c). In the light of the problems under consideration, the so-called secondary ore concentrations, which are related in origin to ore-forming fluids, and as a result, are subordinated to other factors but not to "the formation of primary concentrations," are the most interesting. There are two features emphasized by Schatsky (1965b). First, in the platform which appeared during the platform stage, ore deposits are concentrated not only in the sedimentary cover, but also in the basement. Second, it was shown using an example of Pb-Zn-Cu-deposits of the Ozarci and Cannaci uplifts in the North American platform that similar ores can occur at different stratigraphic levels and in different geological formations, i.e., they are related to certain structural elements, but not to geological formations, and were deposited when certain processes influenced the entire sedimentary cover. These observations show that many regularities of ore accumulation should be considered beyond the concept of formational analysis. Moreover, they are better understood from the standpoints of modern and perspective directions in the study of sedimentary covers (sedimentary basins) as permanently evolving (dynamic) structures influenced by diverse processes affecting the entire crust.

Nowadays, formational analysis seems to be discredited in general as a direction of theoretical geology. Principal conclusions in this field, which were of great significance during past investigations of platforms, are complete. It is possible to scrutinize and improve them, but one can hardly expect that this approach may result in anything principally new. The multidisciplinary problem of studying and ranking the sedimentary basins has now come to the forefront. In this approach, the sedimentary basins are considered as systems comprising not only the sedimentary envelope, but the underlying lithosphere horizons as well. These are dynamic systems with active fluid hydrodynamics. Their development does not cease with the final stage of sediment accumulation, but continues permanently even after sedimentation, and also includes the entire spectrum of interaction processes between the sedimentary cover, consolidated basement, and deeper lithosphere horizons. These are: secondary, epigenetic (in a wide sense) rock alternations; metamorphism at every level of the crust and sedimentary cover; elision and infiltration phenomena; substance redistribution with subsequent concentration in the form of ore and other deposits; and fluid circulation. This direction requires more sensitive methods of study rather than formational analysis, namely the methods of geodynamics, lithology, geochemistry, and mathematical simulation.

TECTONIC PHASES, NEOCATASTROPHISM CRITICS. MOBILISM CRITICS

Schatsky's treatment of some conceptual problems of geotectonics concerning, to some extent, platform tectonics, is interesting in terms of his methodology.

The conception of tectonic phases (orogenic or folding phases) is related to the problems of platform tectonics in two aspects: (a) the presence (or absence) of tectonic impulses common (contemporary) for different platforms, as well as for platforms and mobile belts; and (b) subsequent solving of the question as to whether there are (or are not) global rhythms of movements or episodic global impulses, which is principally important for understanding the causes and mechanisms of the global tectogenesis including the plate tectonic concept.

Schatsky's negative attitude towards Stille's idea on tectonic phases, which Schatsky called "neocatastrophism," is well-known (Schatsky, 1951, and other works). In his opinion, there were no particular phases of tectonic activity (orogeny, folding), only epochs of more intense movements and deformations, which existed in the past, but were of regional and not general, global character. It is necessary to note, that this problem was analyzed by Schatsky for some regions (southeastern Caucasus, and other), but he did not consider the global data base, and his conclusion regarding the absence of global phases was chiefly speculative.

The discussion of tectonic phases is still vital. It seems, however, that the stumbling block is, on the one hand, due to inflexible support, and on the other hand, the similarly rigid refutation of Stille's formulation. Looking at the problem less strictly, i.e., understanding the phases as the epochs of increased tectonic activity in their different forms (Schatsky accepted this at the regional level as was mentioned above), and excluding *a priori* suggestions on the phase duration from their definition, one would not deny the synchronous tectonic events of global rank. This problem was considered recently, in the principal form and with concrete materials, in the works by Leonov and Khain (*Problemy* ..., 1980). Their purpose was to show that the synchronous activity of tectogenesis is distinguishable in different platforms and mobile belts, thus evidencing the global character of tectonic events during some intervals of geological history. It is possible to quote other works as well, all stressing the great importance of the synchronous periods of active tectogenesis in different platforms and lithosphere plates (Khain and Seslavinskii, 1994; Klein, 1991). These data do not confirm Schatsky's viewpoint.

As in the case of tectonic phases and neocatastrophism, Schatsky was unconditionally against mobilism ideas, emphasizing the unsoundness of A. Wegener's views, which were inconsistent with data on the crustal development and structure (Schatsky, 1946b). In light of the present data, his position naturally was not progressive. However, it is necessary to bear in mind that Wegener's hypothesis was an attractive but speculative conception judging from what was known in the middle of century. In addition, the idea suggesting the sial sliding above the simatic layer, rejected by Schatsky, has also been abandoned.

The aforementioned leads to the following discussion. On the one hand, Schatsky was a scientist of the highest standard, creating new directions in science and forming a bright scientific school; but, on the other hand, time showed him to be an antagonist of a number of promising concepts, which went on to form the basic ideas of modern geotectonics, such as those on mobilism, tectonic phases, and nappe tectonics, which were later used as the basis to create the concept of the earth crust tectonic stratification. Using Schatsky's scientific legacy, it is possible to see that he was among the scientists who adhere chiefly to the inductive method, passing from the particular to the general, from facts to an idea, and believe that facts should be numerous enough to corroborate the idea at the stage of its formulation. Scientists of this type contribute many constructive ideas to science if they have real talent, despite the resultant correctness or incorrectness of the conceptual viewpoints. Schatsky and his attitude towards mobilism is an excellent example. Wegener was a scientist of an opposite kind, in terms of his concept of the continental drift. In this case, an idea, or concept was created intuitively on the grounds of data insufficient for complete corroboration. If his intuition was not

wrong, the idea becomes an integral part of the scientific reserve and sometimes may instigate a revolution in science. In the opposite case, both the idea and author's name are soon forgotten.

All this suggests an edifying conclusion. At all times, there is a constructive, basic part in science, where theories and generalizations are based on factual material and, in principal, may be proved or disproved. In addition, there is usually a general ideology, i.e., the conceptions, suggestions, and ideas accepted or refuted intuitively, on the base of general views and scientific addictions. The mobilism of Schatsky's lifetime is an example. The progress in science and our knowledge consistently shifts the boundary between these basic and ideological spheres. Thus, the merit and magnitude of a scientist should not be estimated based on his ideological views, which could be, from the standpoint of the future, either advanced or conservative without a detriment to science. However, this will continue, for some time, and when this or that problem passes from the ideological to the constructive sphere, the position of a scientist may retard or accelerate its solution.

CONCLUSION: MODERN PRIORITY DIRECTIONS IN THE STUDY ON PLATFORM TECTONICS

Schatsky's interests, which are listed in the introduction to this paper, reflect the principal directions in the sphere of platform tectonics during his time. Some of them, such as the study on geological formations, which for a long time was a central focus in geotectonics and other geological disciplines, have now fallen into the background; the others became the commonly used methods of study (comparative tectonic analysis); and one more group is still under development (inheritance problems, aulacogens and others) although they do not, in all aspects, follow the approach of Schatsky (inheritance problems). Of course, after 30 - 40 years, the urgent goals of tectonics changed as one should expect, and this difference is evident from the list presented below. It is difficult to compile a universally acceptable list. No doubt, each investigator may correct and supplement it to a certain extent. I think, however, that basically the list adequately reflects the priority directions in platform tectonics inferable at present and having a certain perspective. The order of themes listed below does not necessarily represent the ranking of their importance, although I personally would arrange them subjectively, in this very succession:

– Dynamics of sedimentary basins (in a wide sense, as it is characterized above under the heading "Formational method");

– Structural features and tectonic processes in different crustal layers of the basement and its cover within different structural elements of platforms; interaction and interdependence of processes on different depth levels. I put emphasis here on (a) the tectonics of the lower and intermediate crust, (b) the basement activity and its consequences in the cover, and (c) the deformation and metamorphism of the sedimentary cover;

– Substance: its sources, redistribution and concentration of sedimentogenesis and epigenesis; hydrothermal activity, ore accumulation, hydrocarbon accumulation. This problem is closely related to both of the problems mentioned above;

– Recent and ancient stress fields; their use in reconstructing geodynamic conditions;

– Tectonic history and shield geodynamics;

– Geodynamic interaction of platforms with mobile belts and general kinematics in the system of lithosphere plates;

– Rifting: deep structure, mechanisms of rift development, causes of rifting and their connection with global processes.

Finally, despite their specific features, platforms are not separate elements. Rather, they are parts of lithosphere plates, connected closely with the plate behavior in geodynamic and geokinematic respects. Therefore, many aspects of platform tectonics are more easily understood when they are studied rather than isolated in a wider context of intraplate tectonics.

Reviewer M.A. Semikhatov

REFERENCES

Dedeev, V.A., Berkovskii, A.N., and Zapol'nov, A.K., Inner Structure of the Russian and Timan-Pechora Plate Basement and Main Stages of Its Formation, *Tektonika Fundamenta Drevnikh Plit* (The Basement Tectonics of Ancient Plates), Moscow: Nauka, 1973, pp. 21 - 29.

Garbar, D.I. and Trofimov, O.V., Geodynamic Analysis of the Baikal Shield Development, *Sov. Geol.*, 1990, no. 10, pp. 56 - 62.

Genshaft, Yu.S., Physical-Mechanical Nature of Tectonic Mobility of the Platform Lithosphere, *Geotektonika* (in press).

Khain, V.E. and Seslavinskii, K.B., Transgressions and Regressions of Seas on Continents during Phanerozoic, *Stratigr. Geol. Correlation*, 1994, vol. 2, no. 6, pp. 520 - 541.

Kheraskov, N.P., *Tektonika i Formatsii: Izbrannye Trudy* (Tectonics and Formations: Selected Works), Moscow: Nauka, 1967.

Klein, G. de V., Origin and Evolution of North American Cratonic Basins, *South Afr. J. Geol.*, 1991, vol. 94, no. 1, pp. 3 - 18.

Peive, A.V., Yanshin, A.L., Zonenshain, L.P., *et al.*, Formation of the Continental Earth Crust of Northern Eurasia (Concerning the Compilation of a New Tectonic Map of Asia) *Geotektonika*, 1976, no. 5, pp. 6 - 23.

Problema Global'noi Korrelyatsii Geologicheskikh Yavlenii (The Problem of Global Correlation of Geological Phenomena), Moscow: Nauka, 1980.

Schatsky, N.S., Principal Tectonic Features of the Siberian Platform, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1932, vol. 10, nos. 3 - 4, pp. 3 - 34. (Selected Works, vol. 2, pp. 195 - 228).[1]

[1] In parentheses, there is a reference to volume and pages in Schatsky, N.S., *Izbrannye Trudy* (Selected Works), Moscow: Nauka, 1964, vol. 2; 1965, vol. 3.

Schatsky, N.S., Tectonics of the East European Platform, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1937a, vol. 15, no. 1, pp. 4 - 27. (Selected Works, vol. 2, pp. 229 - 250).

Schatsky, N.S., Origin of the Donetsk Basin, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1937b, vol. 15, no. 4, pp. 3 - 21. (Selected Works, vol. 2, pp. 251 - 270).

Schatsky, N.S., The Problem of Age of Fold Basement in the Russian Platform, *Sov. Geol.*, 1940, no. 10, pp. 5 - 10. (Selected Works, vol. 2, pp. 278 - 283).

Schatsky, N.S., Comparative Tectonics of North America and Eastern Europe, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1945a, no. 4, pp. 10 - 26. (Selected Works, vol. 2, pp. 459 - 474).

Schatsky, N.S., Essays on Tectonics of the Volga-Urals Oil-Bearing Region and Adjacent Part of the Western Slope of the Southern Urals, *Materialy k Poznaniyu Geologicheskogo Stroeniya SSSR, Novaya Ser.* (Materials for the Study of the USSR Geological Structure, New Ser.), Moscow: Akad. Nauk SSSR, 1945b, vol. 2, no. 6, pp. 56 - 114. (Selected Works, vol. 2, pp. 288 - 368).

Schatsky, N.S., Principal Features of Structure and Development of the East European Platform: Comparative Tectonics of Ancient Platforms: Paper 1, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1946a, no. 1, pp. 3 - 51. (Selected Works, vol. 2, pp. 369 - 425).

Schatsky, N.S., Wegener's Hypothesis and Geosynclines, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1946b, no. 4, pp. 7 - 21. (Selected Works, vol. 2, pp. 601 - 615).

Schatsky, N.S., The Great Donbass and Wichita System: Comparative Tectonics of Ancient Platforms: Paper 2, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1946c, no. 6, pp. 57 - 90. (Selected Works, vol. 2, pp. 426 - 468).

Schatsky, N.S., Structural Connections of Platforms with Geosynclinal Regions: Comparative Tectonics of Ancient Platforms: Paper 3, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1947, no. 5, pp. 37 - 56. (Selected Works, vol. 2, pp. 405 - 522).

Schatsky, N.S., Orogeny and Foreland, *Novye Knigi za Rubezhom*, 1950, no. 12, pp. 19 - 21. (Selected Works, vol. 2, pp. 694 - 696).

Schatsky, N.S., Meso-Cenozoic Tectonics of Central Kazakhstan and West Siberian Lowland: The Problem of Inheritance Phenomena and Platform Development, *Voprosy Litologii i Stratigrafii SSSR* (The Problems of the USSR Lithology and Stratigraphy), Moscow: Akad. Nauk SSSR, 1951a, pp. 232 - 252. (Selected Works, vol. 2, pp. 554 - 573).

Schatsky, N.S., The Duration of Orogeny and Orogenic Cycles, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1951b, no. 1, pp. 15 - 53. (Selected Works, vol. 2, pp. 616 - 653).

Schatsky, N.S., Introduction to the Book by A. Early Structural Geology of North America, *Izbrannye Trudy* (Selected Works), Moscow: Nauka, 1964, vol. 2, pp. 701 - 707.

Schatsky, N.S., Origin of the Pachelma Depression: Comparative Tectonics of Ancient Platforms: Paper 5, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1955a, vol. 30, no. 5, pp. 6 - 26. (Selected Works, vol. 2, pp. 523 - 543).

Schatsky, N.S., Phosphorite-Bearing Geological Formations and the Classification of Phosphorite-Bearing Deposits, *Soveshchanie po Osadochnym Porodam* (Conf. on Sedimentary Rocks), Moscow: Akad. Nauk SSSR, 1955b, vol. 2, pp. 7 - 100. (Selected Works, vol. 3, pp. 52 - 143).

Schatsky, N.S., Parageneses of Sedimentary and Volcanogenic Rocks and Geological Formations, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1960, no. 5, pp. 3 - 23. (Selected Works, vol. 3, pp. 153 - 174).

Schatsky, N.S., Depressions of the Donetsk Type, *Izbrannye Trudy* (Selected Papers), Moscow: Nauka, 1964, vol. 2, pp. 544 - 553.

Schatsky, N.S., Geological Formations, *Izbrannye Trudy* (Selected Papers), Moscow: Nauka, 1965a, vol. 3, pp. 7 - 12.

Schatsky, N.S., Regularities of the Occurrence of Ore Deposits in Platformal Regions, *Izbrannye Trudy* (Selected Papers), Moscow: Nauka, 1965b, vol. 3, pp. 185 - 190.

Schatsky, N.S., Sedimentary Geological Formations, *Izbrannye Trudy* (Selected Papers), Moscow: Nauka, 1965c, vol. 3, pp. 175 - 184.

Tektonicheskaya Karta SSSR i Sopredel'nykh Stran, 1 : 5 000 000, GIN, VSEGEI (Tectonic Map of the USSR and Neighboring Countries, 1 : 5 000 000, GIN, VSEGEI), Schatsky, N.S., Ed., Moscow: Gosgeoltekhizdat, 1956.

Zykov, D.S., Features of the Late Holocene Tectonic Activities in Central Karelia, *Vestn. Mosk. Univ., Ser. Geol.*, 1991, no. 5, pp. 72 - 75.

Stratigraphy and Geological Correlation, Vol. 3, No. 6, 1995, pp. 552 - 558. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 3, No. 6, 1995, pp. 25 - 32.
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N. S. Schatsky's Concept on the Baikalian Folding and the Baikalian Era of Tectogenesis

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Abstract – The history of the notion of the Baikalian folding referred by Schatsky to the end of the Proterozoic - beginning of the Paleozoic, is considered. The review shows that it is actually the Baikalian era of tectogenesis that should be considered, as it spanned the vast interval from 100 to 500 Ma, manifesting in different forms in every continent. It was an era of tectogenesis in the Neogea, which followed the Grenvillian and preceded the Caledonian eras.

Key words: *Baikalian folding, Baikalian era of tectogenesis*

The history of the problem. Establishing a new Baikalian folding epoch in the mid-30s, Schatsky (1935) filled a huge gap in the tectogeneses chronology, which appeared after M. Bertrand, who in 1897 distinguished the Huronian folding, and the Caledonian and later orogenic events. In 1957, Schatsky highlighted the importance of recognizing a new folding epoch, and pointed out that "Baikalian movements resulted in the attachment of consolidated areas, which were comparable in size to those of the Caledonian epochs to older cores" (Schatsky, 1957, p. 587).

To restore the historical truth, we should point out that the term "Baikalian folding" was introduced 10 years earlier by Ya.S. Edelshtein (1923), the Russian explorer of Siberia, and had the same sense and the same factual substantiation as Schatsky suggested. In this regard, it is interesting to quote the work of Edelshtein, where he rightly marks the relative role of the Baikalian and Caledonian tectogeneses in the structural evolution of the southern borderland of the Siberian platform. He wrote, "In the vast area extending from the Aldan River southwestward through the Patom and Vitim uplands, in the Yenisei Ridge, West Sayan and Kuznetsk Alatau, we have baren sedimentary layers probably of Precambrian age, which were subjected to an intense folding and, in places, to high regional metamorphism." The fact that these layers, in areas, (in the Yenisei taiga, some parts of the Baikal areas, in the Aldan River upper course, i.e., in a few regions which were probably subjected to the Archean folding) are unconformably overlain by the Lower Cambrian deposits provides grounds to assign the onset of folding at least to the Algonkian, especially because traces of continental hiatus were also found within these metamorphic sequences in the form of conglomerate interlayers and angular unconformities. Moreover, when baren sequences are unconformably overlain by the Lower Cambrian deposits, the latter are always subjected to an intense folding. This is typical of the Baikal region, Krasnoyarsk area, eastern part of the Minusinsk region and the western slope of the Kuznetsk Alatau. Therefore, we have reason to believe that from the latest Precambrian, i.e., the Algonkian, to the end of the first half of the Paleozoic, at least two orogenic cycles occurred, both separated by immense regressions and subsequent transgressions. Thus, the vast areas of the Precambrian folding were subjected to a subsequent cycle of the Late Paleozoic orogeny. The influence of this cycle extended further west, up to Lake Balkhash, and eastward, nearly up to the Sea of Okhotsk coast. As a result, a huge system of folded mountains appeared at the beginning of the Devonian, forming the principal framework of mountainous Siberia. In the time of finite formation, the system corresponds to those ancient fold massifs of Central Europe, which are known in geology as the Caledonian mountains. Delonet offered this term to be applied for Siberia, but neither the patterns of geographic distribution of these folds he presented, nor the most ancient core of the Asian continent as E. Suess depicted it, fit the picture emerging from the new data available. Moreover, one cannot argue that we have no reliable data for a strict chronological correlation of orogenic phases in Siberia with orogenic cycles in Europe. Therefore, to avoid misunderstanding, we think that different terms would be preferable for Siberia as temporary working terms, and suggest to name, with the just mentioned stipulation, the oldest Precambrian orogenic cycle and resulting folds as the Baikalian, and to designate the late Paleozoic orogenic cycle and related fold complexes as the Yenisean.

Schatsky probably did not know the views of Edelshtein. He had mentioned as his predecessor in this problem only V.A. Obruchev, who revealed in 1926 that intense dislocations in Siberia and northern Asia occurred at the end of the Precambrian. Citing this information, we do not mean to discredit Schatsky in

distinguishing the new major folding epoch, or, to be more exact, the global era of tectogenesis as it will be discussed further on. Almost every explorer has predecessors, including Darwin and Wegener, but the main credit must go to the scientist who succeeds in a complete substantiation of a discovery, making it available for many researchers.

In addition to predecessors in his own country, Schatsky had "competitors" abroad. The most prominent among them was H. Stille, a German tectonist, who singled out the Assyntian tectonic era in 1944 and provided a more detailed substantiation in his works issued in 1946 and 1949, and especially in his monograph in 1958 (Stille, 1958), which was later published in Russian with thorough concluding remarks by Bogdanov and Khain (Stille, 1968). Stille named the era after the Assynt Lake in Scotland, the area representing, in Stille's opinion, the tectonotype of this folding. This tectonotype appeared to be a poor choice. The Assynt Lake area is located in the foreland of the British metamorphic Caledonides; the Lower Cambrian rocks occur here with a hiatus and minor unconformity on the Torridonian clastic continental sequence, which was formed during the rifting stage in the evolution of the Laurentia passive margin. In his latest work, Soper (1994), a British geologist, showed that this unconformity may be classified as the breakup unconformity, which usually separates the rifting and postrifting complexes of continental passive margins. Thus, Stille distinguished the Assyntian folding on the basis of criteria different from those used by Bertrand for discriminating the Caledonian, Hercynian and Alpine foldings, and by Schatsky for the Baikalian, because these were all terminal in the formation of geosynclinal, but not rifting complexes.

In Schatsky's opinion, another imperfection of Stille's concept of the Assyntian tectogenesis is his conclusion that "after the Assyntian folding, none of the crustal parts subjected to these movements were consolidated, and the entire area of the Assyntian folding was regenerated." However, this reproach is unattributable to the monograph issued in 1958, because the first figure in it represents areas which remained consolidated after the Assyntian folding, including the southern periphery of the Siberian craton.

Nevertheless, in terms of priority, selection of tectonotype and evaluation of its importance, the Schatsky concept on Baikalian orogeny offers advantages over the Stille concept on Assyntian tectogenesis. It is not by chance that the term "Assyntian folding" had quickly gone out of use in literature.

The Cadomian folding, recognized for the Armorican massif in 1931 as a concluding phase for the accumulation of the typically geosynclinal Brioverian complex of the Late Proterozoic, has every reason to be a competitor to the Baikalian folding. However, the term "Baikalian folding," as mentioned above, appeared as early as 1923; further, as Stille pointed out, relationships between the Brioverian and Cambrian long remained unclear. Lastly, French researchers of Armorica attached only a regional importance to the Cadomian folding, although in recent years this term became applicable for all of Western Europe.

Several more synonyms for Baikalian folding have been introduced. The term "Panafrican orogeny," suggested by English geologist Kennedy (1964), was the most popular among them. This popularity was, in part, related to the inadequate meaning of the term comprising both the postgeosynclinal folding and a widely developed tectonothermal reworking of an older basement in Africa, and corresponding to the wide time span from 950 to 500 Ma (the last value was introduced by Kennedy, with "±" sign). An analog of the Panafrican orogeny in South America is the Brazilian orogeny, which local geologists compare to the Baikalian.

Thus, the term "Baikalian folding," or more exactly "Baikalian era of tectogenesis," is the most preferable from every point of view to designate tectonic movement, which occured at the very end of the Precambrian and very beginning of the Paleozoic.

We should emphasize, however, that in recent Russian literature it has been questioned whether or not the terms "Baikalian folding" and "Baikalides" are rightful. The doubts are based on the fact that in the Baikal region, where the tectonotype of the Baikalides must be located, this folding is clearly identified, and the leading role belongs to Caledonian deformations; however, this is true in general. Here we should recall that Edelshtein wrote: "the areas of the Precambrian folding were subjected to a subsequent cycle of at least the early Paleozoic orogeny." Nevertheless, manifestation of the pre-Vendian or pre-Cambrian unconformity, which is marked by the metamorphism and granite formation of the Lesnoi complex of K-Na granitoids dated as 556 ± 16 Ma old and plagiogranites of the Maloyakornyi complex dated as 537 ± 9 Ma old, (the U-Pb method on zyrcons, Sryvtsev *et al.*, 1992), is undeniable. In the Patom highland, the older age (Yazov granitoid complex of 730 ± 97 Ma) is revealed by the U-Pb zyrcon method (data by A.M. Larin and A.L. Neimark submitted to the monograph *The Precambrian of the Patom Upland* in 1995). Thus, even if the tectonotype and name of the era of tectogenesis selected were not quite correct, as it happened both with the stratotype and petrotypes (for instance to gabbro and syenites), the global implication of the era is beyond question.

CHRONOLOGICAL BOUNDARIES OF THE BAIKALIAN ERA OF TECTOGENESIS

Very often, chronological boundaries of the Baikalian folding are interpreted to be narrow, directly preceding the Cambrian. Such an interpretation disagrees with the views of Schatsky, who, when criticizing Stille, wrote that "closure of the Assyntian geosyncline was during a single phase, at the boundary between the

Cambrian and Proterozoic" (actually, in addition to the late Algonkian, Stille pointed out two inter-Algonkian phases of deformations). "As I often pointed out," Schatsky wrote further on, "the orogeny at the boundary between the Cambrian and Proterozoic, as well as during other periods, lasted for a long time, and, in particular, major Baikalian movements took place at the beginning of the Cambrian, and subsequently after the Early Cambrian but prior to the Late Cambrian time." We should operate with this wide definition, and consider that the Baikalian era of tectogenesis spans the entire time interval from the end of the Grenvillian era to the beginning of the Caledonian era proper.

The first boundary is more easily detectable than the second. Independence of the Baikalian structural patterns relative to the Grenvillian and earlier events is evident almost everywhere. This is not surprising, since the Baikalian orogenic events mark the commencement of a new megaera (megachron, after Schatsky) of Neogea in the earth's history. The end of the Grenvillian orogenic events is dated by values of 1.0 - 0.9 Ga, and respectively, the beginning of the Baikalian events can be assigned to 0.9 - 0.85 Ga.

The situation is more complicated with the boundary between the Baikalian and Caledonian orogenic events, since the end of the former is overlapped by the beginning of the latter. In the classic Caledonides, which are derivatives of the Iapetus Ocean, the entire Cambrian already corresponds to the initial stage in their evolution. The same is true for the Caledonides of central Kazakhstan, northern Tien Shan, and the Altai–Sayan area, as well as for the Lachlandian system of eastern Australia. However, in other fold areas (the Timan–Pechora region, Antarctic Rossides), and generally within the future Gondwanaland in gross, the intra-Cambrian and pre-Ordovician deformations were related to final stages of the Baikalian tectogenesis. Thus, the Cambrian phases of deformations permit a dual interpretation: depending on a general "context" they may be considered either as the late Baikalian or the early Caledonian. Therefore, we included these phases into a subsequent discussion to show their global implication, regardless of some regions where they are variably referred to the Baikalian or Caledonian eras of tectogenesis.

PRINCIPAL PHASES OF THE BAIKALIAN TECTOGENESIS

To reliably distinguish separate phases of the Baikalian tectogenesis, we attempted to generalize statistically the published radiometric ages of granitoid intrusion and metamorphic events of the Late Proterozoic and Cambrian, and to correlate these data with known hiatuses and unconformities. In reaching this goal, we encountered some difficulties which were related to the rocks dated by the radiological method and to a large uncertainty of many age determinations. Moreover, some of the latter admit an ambiguous tectonic interpretation. In addition, some objects attracted more attention from researchers than others, and therefore, a greater number of datings were obtained for these objects. There is no way to avoid the influence of these factors upon the analysis under consideration. We also have to take into account a general increase in the number of age determinations for later tectonic events as compared to older events. However, we hoped that this factor would not distort the real picture for the interval from 1.0 to 0.5 Ga, which is rather far from the present time. In any case, the analyzed data base (about 900 age measurements) is large enough to attest to the objectivity of the compiled histogram (Fig. 1). We used abstracts from *Geology* (1991 - 1994, and nos. 1 - 3, 1995) as a source to obtain age data. Some original papers from foreign journals (issued during 1994 and 1995) were also included in the analysis. The histogram shows a series of essential features of the Baikalian era of tectogenesis, all quite satisfactory correlative with the schemes of tectonic evolution of particular regions on earth. First of all, the histogram depicts a clear peak of endogenic events which occurred about 1.0 Ga ago, i.e., during termination of the Grenvillian stage in the earth's evolution. It is significant that there are many datings for this time interval, similar to events grouped at about 500 Ma, indicating the beginning of the basin opening at the subsequent tectonic stage. A decrease in the number of datings for the interval later than 1.0 Ga, seems to reflect the compression-related events corresponding to the beginning of the Baikalian era of tectogenesis. Available data indicating the tensional processes, most likely the continental rifting, is also very demonstrative. This early interval of the Baikalian tectonic era lasted about 150 Ma and was marked by low activity.

The interval about 850 Ma ago. The first tectonic phase, well identified on the histogram, was in the middle Late Riphean, about 850 Ma ago. Earlier, Khain proposed to call this phase "Delhian" on the basis of its role in terminating the evolution of the Delhian folded system in northeastern India. However, this phase occured at 700 Ma rather than 850 Ma ago. On the other hand, the 850-Ma-old phase is well expressed within the Yenisei Ridge, where folding and formation of the Ayakhta granitoid complex, as well as replacement of flysch sedimentation with molasse accumulation, are associated with it. The name "Yenisean" is therefore suitable for this tectonic phase. A characteristic feature of this phase, or epoch, is a close geodynamic interrelation of geological events caused, on the one hand, by the earth's crust compression (folding, formation of granitoids, and regional metamorphism), and on the other hand, by tensional deformations related to the continuing formation of the global oceanic system and ocean-related mobile belts. The first group of events comprises the folding, granitization and metamorphism in the European fragment of the Mediterranean belt (in the Carpathians, Balkanides and Alps); the Jinning folding in South China, the peak of metamorphism in

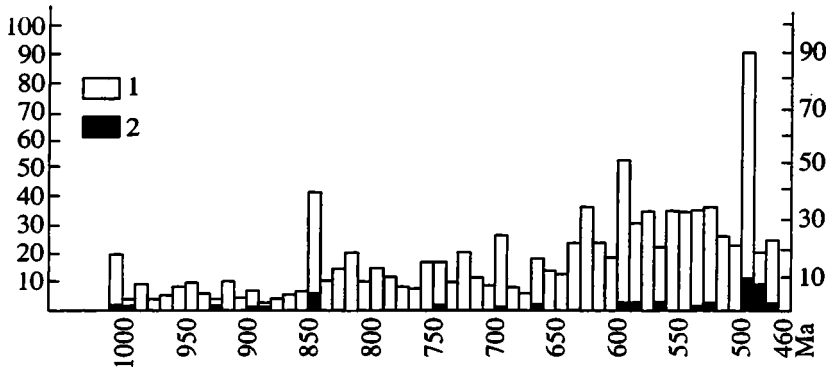

Fig. 1. Histogram of age determinations marking the endogenic activity of the earth in the interval 1000 - 500 Ma. 1 – data for granitoids, calc-alkaline volcanics and metamorphic rocks; 2 – data for ophiolites.

eastern Antarctica, and the Lufilian folding in the African part of the proto-Atlantic belt. Similar deformations caused granitization and metamorphism in the Yenisei Ridge, Bohemia massif, and Indochina. Mossakovskii *et al.* (1993) quoted a close age (830 ± 15 Ma) for the orogenic volcanism in Central Tien Shan.

According to Stewart (1976), a radical reorganization of North American structural patterns was associated with the same tectonic phase. The reorganization involved a general uplift of the central part of the continent, and a transition from isolated depressions and aulacogens to a newly formed passive margin encircling the entire continent.

Destructive processes were best manifested in the formation of ophiolite associations with an age of 850 Ma, known, for example, in the Mauritanides and Anti Atlas, as well as in the Nubia–Arabia region. The presence of these ophiolites indicates the initial opening of ocean basins in the Mediterranean and Arabia–Mozambique mobile belts. Ophiolites similar in age were reported by Mossakovskii *et al.* (1993) from the Central Asian foldbelt near the northern edge of the Korea–China craton. Tensional deformations are also recorded in both continental margins of the proto-Atlantic belt and in the Uralian fragment of the Urals–Okhotsk belt. In both of these cases, oceanic basins completely opened at a later time.

Pre-Vendian events. There is an important tectonic phase at the boundary between the Riphean and Vendian, dated at about 650 Ma ago, though it is unrecognizable on our histogram for reasons not well understood. In the Armorican massif, the unconformity, which provided the grounds to distinguish the Domnonean phase, separates the lower and upper Brioverian. In the Bohemian massif, the same tectonic phase is often called, following Stille, "Zheleznogorian." Outside Europe, traces of this tectonic phase are known in the Turukhansk dislocation zone of the western Siberian platform, in the Arabia-Nubia shield, and in Sri Lanka. The initial spreading in the North Atlantic belt may be considered as one of the probable important tectonic events of an opposite sign, which is proved by the age of the earliest island arc complexes within it (the so-called the Malvernian complex in Wales).

Cadomian (Panafrican) events. These events, which represented a series of tectonic phases, the earliest taking place at the boundary between the Early and Late Vendian about 600 Ma ago, had an important role in the Baikalian tectonic era. As was mentioned above, the events were most prominent in the terminal basement evolution of the Variscides of western and central Europe. The Cadomian tectogenesis was equally important in closing that vast area of the Prototethys which framed the African continent. Within the latter, the tectogenesis was also widely developed, thus affirming the appropriateness of its second name, "Panafrican." The decisive importance of the Panafrican-Cadomian tectonic events for the evolution of the Mozambiquian ocean is also quite evident. This ocean separated the western Gondwana comprising the African continent, from a continental group of the eastern Gondwana, whose closest element was Hindustan. However, the relict epi-Cadomian basins could also survive in this ocean (Kazmin, 1988).

The Cadomian events comprised not only compressive deformations in the crust, but also geodynamically related and compensating tensional movements. The latter could be a continuation of earlier long-lasting processes. This can be exemplified by the progressive evolution of the North Atlantic and a considerable part of the Mediterranean mobile belts. In the North Atlantic belt, the evolution of the Iapetus Ocean was still in progress without principal Cadomian changes, though Coish *et al.* (1991) pointed to the more intense destruction of the eastern margin of Laurentia initiated about 600 Ma ago. Within the Prototethys, the relict basins survived around the Fenno-Sarmatian blocks in Europe and in the Asian segment of the belt, particularly in the Himalayas.

The numerous datings available of the Cadomian level, as well as the vast areas affected by these tectonic events, indicate the important and even leading role of

Epochs of tectogenesis \ Continents	Europe	Asia	Africa	Australia	Antarctica	North America	South America
Salairian	+ × ~	+ × ~ △ ▼	+ ~	× ~ ▼ △	+ × ~ △	△	+ ~ ▼
Cadomian	+ × ~	+ × ~	+ × ~	× ~ △	+ × ~	+ ⊓	+ × ~
Yenisean	× ~ △	+ ~ ▼ △	~ ▼ △	△			~ ▼

+ + 1 × × 2 ~ 3 ⊓ 4 ▼ 5 △ 6

Fig. 2. Continents affected by separate epochs of the Baikalian tectogenesis.
1 – granitoids; 2 – calc-alkaline volcanics; 3 – regional metamorphism; 4 – tectonothermal reworking; 5 – spreading; 6 – continental rifting.

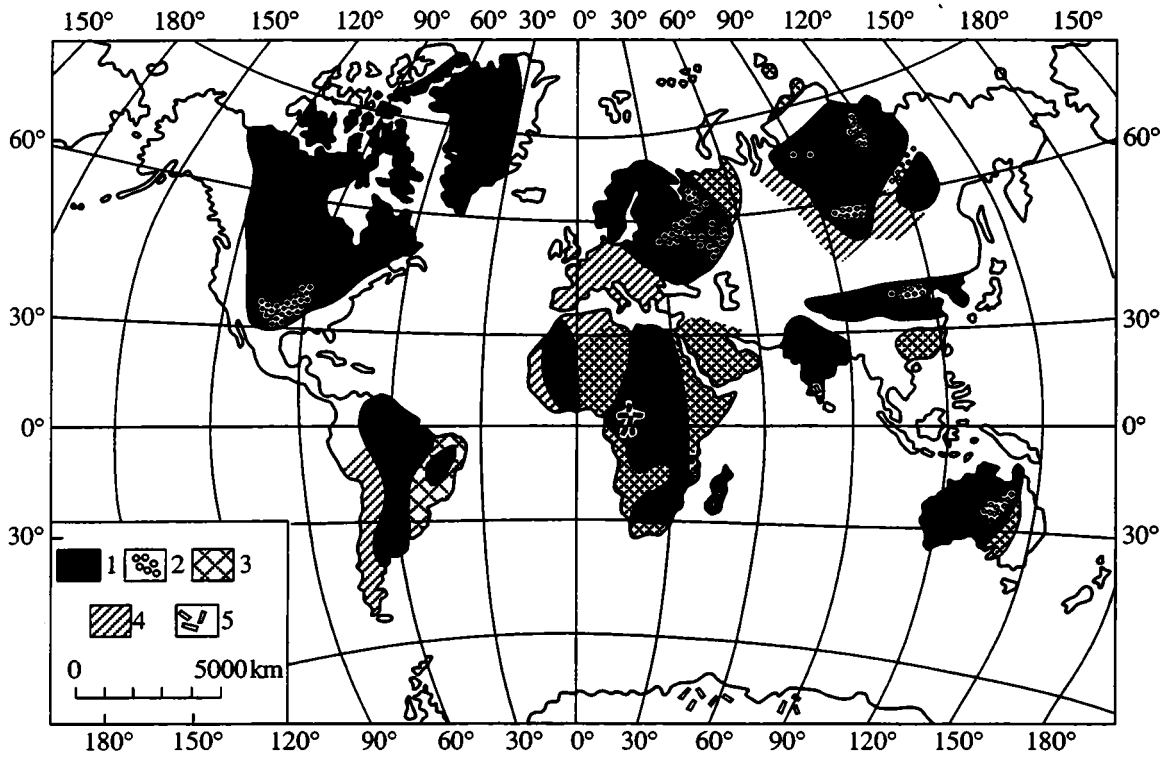

Fig. 3. Regions of the Baikalian tectogenesis.
1 – pre-Baikalian cratons; 2 – rifting zones in ancient cratons; 3 – zones of the Baikalian tectogenesis later experienced the complete consolidation; 4 – zones of the Baikalian tectogenesis with regenerated mobility; 5 – zones of tectonothermal reworking of the pre-Baikalian continental crust.

this epoch in the Baikalian tectonic era. In particular, the histogram shows and real geological information proves that the Cadomian, or Panafrican (*s.s.*) epoch about 600 Ma ago was followed by an epoch of intense tectonic activity, which lasted until the Salairian folding phase. Such a character of this late Baikalian tectonic epoch is reflected in the fact that in foreign literature, the long-term events, up to 500 Ma, are often called Panafrican (*s.l.*). We may state that the Cadomian epoch (*s.s.*) was initial for the intense tectonic activity at the end of the Baikalian tectonic era. On the other hand, there are many regions where Cadomian events were insignificant. For instance, no considerable changes of that time are distinguishable in the course of the evolution of the Himalayan basin of the Prototethys. They were also unimportant within the Paleoasian ocean, whose opening in the Vendian and Early Cam-

brian is evident from age determinations of ophiolites in the Altai–Sayan area and western Mongolia.

In contrast to the compiled histogram, the paleotectonic studies revealed an independent pre-Cambrian tectonic phase, which, according to recent data, is referable to the interval of 550 - 540 Ma. Important events of this time were recorded in Western Europe (the British Midland and Central massif of France), Asia (Sri Lanka), Central Australia and in the Transantarctic Mountains.

Salairian events. Surprisingly, the Salairian tectonic events appear to mark one of the most salient turning points in the early Paleozoic history of the earth at the transition from the Baikalian to the Caledonian tectonic era. These events occurred at the end of the Middle Cambrian and very beginning of the Early Ordovician. Their peak of tectonic activity falls at 500 Ma. The importance of the Salairian events is evident from several viewpoints. First, the Salairian hiatuses and unconformities are frequent. This was already recognized by A.A. Pronin (1969), who noted the hiatuses between the Cambrian and Ordovician strata in 95% of all sections analyzed by him, which were located in different regions of the world.

Second, results of the Salairian events are recorded in all continents, including Antarctica. It is also important that these events are evident in the evolution of very different tectonic elements. The area affected by the Salairian events of tectogenesis appears to be much larger than that of the Cadomian epoch, as the former were also manifested, though in different but quite natural forms, in areas where the Cadomian epoch coincides with a crisis in the earth's evolution. Many regions of North Africa are good examples. On the other hand, in oceanic basins, where spreading was still in progress at the beginning of the Paleozoic, the Salairian tectonic impulse often resulted in the imbrication of tectonic elements, and formation of volcanic arcs could be one of the consequences of this process. Similar events are registered in the Kazakhstan–Tien Shan (Dergunov, 1989) and South Siberian (Mossakovskii *et al.*, 1993) segments of the Paleoasian Ocean.

Third, in addition to dominant compressive deformations, the Salairian phase caused considerable tectonic tension in some areas, which either resulted in the replacement of continental rifting by spreading, or kept the ocean basin evolution in progress. Events of the first type can be distinguished in evolution of the Uralian fragment of the Urals–Okhotsk belt (Puchkov, 1995), whereas in the North Atlantic, the earlier opening of the Iapetus seems to become more intense, as is evident from the age determinations for ophiolites in the Shetland Islands (495 and 498 Ma) (Flinn *et al.*, 1991) and Appalachians (489 Ma) (Dunning and Krogh, 1991). The opening of the earliest basins, which later united into the Paleotethys, was recorded in the Shamruss ophiolites (496 Ma) and Western Alps. Similar events occurred in the Central Kazakhstan and Tien Shan basins of the Paleoasian ocean. For some zones of Tien Shan, the time of ophiolite formation corresponds, according to paleontological data, to the Late Cambrian-Early Ordovician (Demina *et al.*, 1995). Events, which were related to strain fields with opposite signs, suggests their geodynamic interrelation and compensating character.

Fourth, the Salairian epoch comprised many drastic changes in the global tectonic evolution. Several of them are remarkable. The complete closure of relict basins of the European Prototethys and the Mozambique ocean occurred during the Salairian epoch. However, the first event, which resulted in the short-term attachment of the Arabian-African continent to Eastern Europe, could have happened earlier, as the basins' opening in the incipient Paleotethys started during the earliest Ordovician. The closure of the Mozambique ocean created the single Gondwana supercontinent after the final collision of the western and eastern continental masses of Gondwana, which commenced during the Cadomian folding. Separation of the Laurentia continent from these continental masses, which also occurred about 500 Ma ago (Moyes *et al.*, 1993), was a geodynamic consequence of the Gondwana formation. This event differentiated tectonic regimes in Laurentia and Gonwanaland, the former characterized by the prevalence of destructive processes during the Early Paleozoic (Johnson, 1994). The same Salairian tectogenesis led to the closure of ocean basins in several regions, such as the eastern part of the Urals–Okhotsk mobile belt, the Mediterranean belt (Himalayan basin), the western zone of the Lachlandian system of eastern Australia, and the Transantarctic mobile belt. In the North Atlantic mobile belt, the Salairian tectonic epoch was marked by less notable, but still important changes in evolution of this region, where a series of marginal basins was closed due to Grampian and Finnmarkian tectogeneses. Thus, in its impact on the global evolution of the lithosphere, the Salairian epoch exceeds other epochs of the Baikalian tectonic era, including the Cadomian (Panafrican) tectogenesis. The importance of Salairian events is also evident from the fact that this short interval comprised a wide range of tectonic reorganizations, such as the transition from rifting to spreading; the considerable widening of ocean basins, which opened earlier; the local imbrication of the earth's crust resulted in formation of island arcs; the partial or complete closure of some basins; and coupling of major continental masses.

The Salairian maximum of age determinations presented in the histogram is restricted in duration and concentrated. In contrast, the post-Salairian time shows an abrupt decrease in the number of age determinations. Such a distribution indicates that Salairian events were terminal in the Baikalian tectonic era. This confirms Schatsky's conclusion that "the Cambrian movements are not the beginning of the Caledonian, but the end of the Riphean movements" (Schatsky, 1957, p. 597).

The aforesaid may not eliminate the possibility that the Salairian events had somewhat different significance in certain regions.

CONCLUSION

Thus, all new data, which were accumulated after Schatsky's basic work was issued 60 years ago, fully proved the importance of his idea on the Baikalian folding epoch assigned to the end of the Precambrian - beginning of the Paleozoic. The data suggest that it was the Baikalian era of tectogenesis comprising the interval of 1000 - 500 Ma between the Grenvillian and Caledonian eras. The global importance of this epoch is evident, as tectonic events affected every continent, though manifested in different forms even within the same continent (Figs. 2 and 3).

REFERENCES

Coish, R.A., Bramley, A., Gavigan, T., and Masinter, R., Progressive Changes in Volcanism during Iapetan Rifting: Comparison with the East African Rift-Red Sea System, *Geology,* 1991, vol. 19, pp. 1021 - 1024.

Demina, L.I., Lomize, M.G., and Avdonin, A.V., Geochemical Characteristics of the Prisongkel'ya Peridotites (northern Tien Shan), *Vestn. Mosk. Univ., Geol.*, 1995, no. 1, pp. 91 - 99.

Dergunov, A.B., *Kaledonidy Tsentral'noi Azii* (Caledonides of Central Asia), Moscow: Nauka, 1989.

Dunning, G.R. and Krogh, T.E., Stratigraphic Correlation of the Appalachian Ordovician Using Advanced U-Pb Zircon Geochronology Techniques, *Pap. Geol. Surv. Can.*, 1991, no. 90-9, pp. 85 - 92.

Edelshtein, Ya.S., Tectonics and Mineral Resources of Siberia, *Izv. Geol. Com.*, 1923, vol. 42, pp. 23 - 50.

Flinn, D., Miller, J.A., and Roddon, D., The Age of the Norwick Hornblendic Schists of Unst and Fetlar and the Obduction of the Schetland Ophiolite, *Scot. J. Geol.*, 1991, vol. 27, no. 1, pp. 11 - 19.

Johnson, P.R., Zietz, I., and Thomas, W.A., Possible Neoproterozoic - Early Paleozoic Grabens in Mississipi, Alabama, and Tennessee, *Geology*, 1994, vol. 22, no. 1, pp. 11 - 14.

Kazmin, V.G., Tectonic Evolution of the Mosambique Belt: from Accretion to Collision, *Geotektonika*, 1988, no. 3, pp. 26 - 34.

Kennedy, W.Q., The Structural Differentiation of Africa in the Pan-African (±500 Ma) Tectonic Episode, *Annu. Rep. Res. Inst. Afr. Geol., Univ. of Leeds*, 1964, vol. 8, pp. 48 - 49.

Mossakovskii, A.A., Ruzhentsev, S.V., Samygin, S.G., and Kheraskova, T.N., Central Asian Paleozoic Foldbelt: Geodynamic Evolution and Formation History, *Geotektonika*, 1993, no. 6, pp. 3 - 32.

Moyes, A.B., Barton, J.M., and Groenwald, P.B., Late Proterozoic to Early Paleozoic Tectonism in Droning Maud Land, Antarctica: Supercontinental Fragmentation and Amalgamation, *J. Geol. Soc. London*, 1993, vol. 150, no. 5, pp. 833 - 842.

Pronin, A.A., *Kaledonskii Tsikl Tektonicheskoi Istorii Zemli* (Caledonian Cycle in the Earth's Tectonic History), Leningrad: Nauka, 1969.

Puchkov, V.N., Correlation of Stages in Tectonic Evolution of the Volga-Urals Oil Province and the Ural Western Slope, *Tektonika Osadochnykh Basseinov Severnoi Evrazii* (Tectonics of Sedimentary Basins in Northern Asia), Moscow: Nauka, 1995, pp. 143 - 146.

Schatsky, N.S., The Relationship between Cambrian and Proterozoic and the Baikalian Folding, *Izbr. Tr., T. 1* (Selected Works, Vol. 1), Moscow: Akad. Nauk SSSR, 1963, pp. 581 - 587 (original issue 1957).

Schatsky, N.S., Tectonics of the Arctic, *Izbr. Tr., T. 1* (Selected Works, Vol. 1), Moscow: Akad. Nauk SSSR, 1963, pp. 426 - 444 (original issue 1935).

Soper, N.J., Was Scotland a Vendian RRR Junction?, *J. Geol. Soc.* (London), 1994, vol. 151, no. 3, pp. 579 - 582.

Sryvtsev, N.A., Khalilov, V.A., Buldygerov, V.V., and Perelyaev, V.P., Geochronology of Granitoids of the Baikal-Muyan Belt, *Geol. Geofiz.*, 1992, no. 9, pp. 72 - 78.

Stewart, J.N., Late Precambrian Evolution of North America: Plate Tectonics Implication, *Geology*, 1976, vol. 4, no. 1, pp. 11 - 15.

Stille, H., *Die assyntische Tektonik im geologischen Erdbild*, Hannover: Amt für Bodenforschung, 1958.

Stratigraphy and Geological Correlation, Vol. 3, No. 6, 1995, pp. 559 - 574. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 3, No. 6, 1995, pp. 33 - 50.
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Methodic Principles of the Riphean Stratigraphy

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Abstract – Riphean stratigraphy, which was born 50 years ago when this stratigraphic subdivision was discriminated by using data of comparative tectonics (historical geology), now utilizes a series of the methods applied in biostratigraphy, isotopic geochronology, chemostratigraphy, paleoclimatology, and paleomagnetic studies. This paper considers the methodic possibilities of four indicated scientific branches for solving chronostratigraphic problems of the Riphean. It also presents a synopsis of data on taxonomic changes in the microfossil and stromatolite assemblages, and on large-scale variations in the C- and Sr-isotope composition of carbonate rocks depicting unique features of successive intervals of the Late Precambrian, each decreasing upward in duration in the section. Specific bio- and chemostratigraphic characteristics of three Riphean erathems and their subdivisions, in combination with data of isotopic geochronology and climatostratigraphy, not only provide the possibility to distinguish and correlate these subdivisions in remote regions, but also create a real and promising perspective to identify them as chronostratigraphic units (to formally determine their lower boundary) by using a paleontological and chemostratigraphic framework.

Key words: *Riphean, Vendian, biostratigraphy, chemostratigraphy, isotopic geochronology, climatostratigraphy, chronostratigraphy, subdivision, correlation*

Schatsky's recognition of the Riphean (Schatsky, 1945, 1952a, 1952b, 1957, 1960) was an important event in the long history of elaboration of the general stratigraphic scale of the Precambrian initiated by R. Irving, S. Emmons, and C. Walcott at the end of the last century. Identifying the Riphean, Schatsky paid significant attention to the large unconformities related to the main folding epochs (the Karelian preceding the Riphean and the Baikalian terminating it). However, his studies were concentrated mostly on the analysis of successive paragenetic associations of supracrustal rocks (formations) and on the comparative tectonic analysis of the earth's history.

Considering the section of pre-Ordovician "barren formations" of the southern Urals from these standpoints, Schatsky concluded that its succession of four unconformably bounded groups (the Burzyan, Yurmata, Karatau, and Asha groups in modern terminology) represents an integrated formation succession similar to those distinguished for the Hercynian and Alpine epochs, and culminated with red molasses of the Asha Group (Schatsky, 1957). All of these deposits were referred to the Upper Proterozoic and termed as the Riphean Group (Schatsky, 1945). Schatsky stressed that the Riphean is separated by a large hiatus from molasses of the last (Karelian) folding phase in the Baltic shield, assigning to these molasses "the Jotnian complex of red formations and their Ukrainian counterpart, the Ovruch Quartzite" intruded by rapakivi granites. Subsequently, in Schatsky's opinion, the Karelian (Svecofennian in modern terminology) molasses included the Vepsian, Sub-Jotnian, and their analogues (the age interval of 1780 - 1680 Ma) undiscriminated at that time from the Jotnian, which is Middle Riphean in age as we presently know. This should be kept in mind when we interpret Schatsky's words (1952a) that suggested the term "Riphean Group" corresponds to all deposits occurring between the Jotnian and Cambrian.

It is remarkable that in contrast to many other Precambrian subdivisions, the recognition of the Riphean appeared along with the identification of the stratotype and boundaries of this new stratigraphic unit. The stratotype suggested was the miogeosynclinal section of the Bashkir anticlinorium of the southern Urals, considered as "one of the sections most completely displaying peculiarities of the Riphean stage in the earth's evolution," while the Riphean boundaries were placed at the base of the Burzyan Group and at the base of the Cambrian (Schatsky, 1945, 1952a, 1952b, 1957, 1960).

Thus, the Riphean was distinguished as a stratigraphic, or in modern terms, chronostratigraphic subdivision. As compared to the now popular chronometric, or less significant, structural and lithostratigraphic principles of Precambrian stratigraphy (for analysis and references, see Semikhatov, 1991, 1993), the above approach is more progressive, because the chronostratigraphic units have to be identified by analyzing the most complete supracrustal sedimentary successions bearing organic remains once the stratotypes of subdivisions are identified and their boundaries are fixed in

specially selected type sections (in global stratotype sections and points). As a result, this approach warrants the necessity of recognized subdivisions and their independence of changing ideas concerning the time span and lithologic features of the units. This provides the possibility to obtain comprehensive (paleontological, eventual, geochronological, chemostratigraphic, paleomagnetic, etc.) characteristics of a subdivision and its boundaries. The tendency to multidisciplinary substantiate general units is a distinct feature of present Phanerozoic stratigraphy which introduced the term holostratigraphy, meaning the solution of stratigraphic problems from every point of view (Walliser, 1986; Cowie, 1989). There are no grounds to believe that the development of ideas and methodic principles of Precambrian stratigraphy (at least for its Proterozoic part) should follow an independent course (Hedberg, 1974; Sokolov, 1979; Semikhatov, 1991, 1993). Moreover, the complex substantiation of stratigraphic concepts is necessary especially for the Precambrian lacking skeleton fauna, which is the basis of stratigraphic zonation for the Phanerozoic.

It is clear from available publications that Schatsky (1948, 1952a, 1952b, 1957) well understood the necessity of a comprehensive approach to Riphean stratigraphy. He ardently supported microphytological studies of the Upper Precambrian, stressed the peculiarity of the Riphean organic kingdom, wrote on the significance of paleontological and geochronological data elucidating the position of the Riphean base, and analyzed specific features of the Riphean sedimentation and environments. It is another matter that in Schatsky's lifetime, all of these studies were at the initial stages. This is the reason why he wrote in 1960: "*at present* (stressing is mine, M. S.) the only method to solve stratigraphic problems of the Upper Precambrian is the tectonics ..., namely, the study of the build-up history of geotectonic elements; elucidating it by using the comparative method, we may arrive at one conclusion or another concerning the evolutionary stages of the earth's surface as a whole" (Schatsky, 1960, p. 6). The subsequent development of this approach invigorated the Riphean to be one of the most important subdivisions of the Upper Precambrian (Keller, 1952; *Stratigrafiya* ...,1963; Keller and Semikhatov, 1968; Semikhatov, 1974). The Vendian, which was distinguished by Sokolov (1952, 1964, 1979), became the next subdivision of this type, and included the uppermost horizons of the Riphean according to Schatsky's original understanding, i.e., the deposits occurring between a base of the Laplandian (Varangerian) glaciohorizon and the Cambrian lower boundary.

As for the applicability of the comparative tectonic (historical-geological) method in detailing the Riphean subdivision (e.g. Keller, 1952; Keller and Khomentovsky, 1960), there were no positive results, because the method itself is useless for an interregional correlation of stratigraphic units distinguished on the basis of tectonic evolution of certain regions, even if such regions are very great (for details, see Semikhatov, 1974, pp. 7 - 21). Schatsky (1960, 1963) expected progress in detailed Riphean stratigraphy to come from other methods, which, he believed, "will be slow to develop."

Schatsky's anxiety was in vain, as it is now clear that 50 years after the recognition of the Riphean we have a series of methods enabling chronostratigraphic studies of this subdivision. These are the methods of biostratigraphy, isotopic geochronology, chemostratigraphy, paleoclimatology, and paleomagnetic study, each with their own advantages and defects. Without analyzing all of the possibilities of these methods in detail, I will consider the main aspects of those which are most important.

BIOSTRATIGRAPHIC METHOD

Precambrian biostratigraphy represents a fast evolving branch of nontraditional biostratigraphy, which deals with the specific study of objects related to the general evolutionary level of the Precambrian bios. The first steps in this direction were made by C. Walcott, C.L. and M.A. Fentons, V.P. Maslov, S.N. Naumova, and B.V. Timofeev (for review, see Krylov, 1963; Krylov *et al.*, 1989; Sergeev, 1992). Since that time, ideas on the potentials of the method, and on the most important groups of Proterozoic organic remains changed many times. Now it is widely accepted that stromatolites and microfossils of different biological affinity provide the basis for Riphean biostratigraphy. However, opinions concerning the stratigraphic potential of these groups are still controversial.

Stromatolites represent layered organio-sedimentary structures attached to the substratum, and originated as a result of trapping, binding, and/or precipitation of carbonate material during the metabolic activity of assembled microorganisms, mostly of cyanobacteria. The first attempts to use stromatolites for stratigraphic correlation were in the 1920s - 1940s, though the stratigraphic significance of their Proterozoic representatives was not shown until the 1960s - 1970s (for review, see Semikhatov, 1974), when these buildups were adequately classified on the basis of their morphological and microstructural features (Korolyuk, 1960; Krylov, 1960, 1963, 1975; Semikhatov, 1962; Raaben, 1964; Komar, 1966), and thus provided, for the first time, reliable information on the space-and-time distribution of columnar stromatolite taxa dominant during the Late Proterozoic. It was demonstrated that the Riphean deposits of northern Eurasia contain unique successions of formal genera (groups) and formal species (forms) of stromatolites, and that in the most complete sections, these successions are divisible into three consecutive complexes correlative in the lateral direction because of a number of common groups and some common forms (for review, see Semikhatov, 1976). These data, in combination with later materials concerning other continents (see Preiss, 1976; Bertrand-Sarfati and

Walter, 1981), provided the basis for the empirical arguments demonstrating the stratigraphic value of the Late Proterozoic stromatolites. This was also proved by similar isotopic (mostly K-Ar) datings for deposits containing taxonomically correlative stromatolite complexes in distantly located sections (Keller *et al.*, 1960; Garris *et al.*, 1964; Semikhatov, 1974).

As a result of these data, an influential opinion emerged that stromatolites enable the general three-unit subdivision of the Riphean (Keller *et al.*, 1960, 1977; Semikhatov, 1962, 1974; Krylov, 1963, 1975, 1985; Komar *et al.*, 1964; Raaben, 1975, 1969; Cloud and Semikhatov, 1969; Bertrand-Sarfati, 1972; Walter, 1972; and others). The fact that in the Uralian stratotype the three aforementioned taxonomic complexes are respectively confined to the types of the Lower, Middle, and Upper Riphean (the Burzyan, Yurmata, and Karatau groups) provided independent paleontological characteristics to these subdivisions, and created an illusion that they are biostratigraphic units with clearly defined boundaries. This illusion is reflected in the term "phythem," which was introduced as appropriate to the units and emphasizing the priority of phytolites (stromatolites and microphytolites) in their recognition (Keller, 1966). However, it was soon realized that this optimistic evaluation of the stratigraphic significance of the Riphean stromatolites had to be revised from both the methodic and factual positions.

Proterozoic stromatolites were confined mostly to carbonate platforms, and this fact, along with the facial specialization of some morphotypes (Serebryakov, 1975; Grey and Thorne, 1985; Grotzinger, 1989; Zhu and Chen, 1992), predetermines the discrete distribution of these microbiolite complexes throughout the sections. In this respect, the Uralian stratotype of the Riphean is not an exclusion, because stromatolites are known here only in the middle and/or upper horizons of all three type sections of the Riphean erathems. Lower boundaries of these subdivisions are traditionally delineated as corresponding to the basal unconformities of terrigenous units, which are basal in the Burzyan, Yurmata, and Karatau groups. It was popular in 1970s to overcome the imperfections of Uralian stratotypes through the use of Siberian sections more saturated with stromatolites to determine the boundaries of the main Riphean subdivision. However, these attempts were unsuccessful. First, without strict criteria to correctly correlate the Uralian and Siberian sections, they risked the inadequate interpretation of stratigraphic ranges of the Riphean subdivisions. Second, they were unable to completely solve problems related to the discrete time distribution of stromatolites usable in stratigraphy. Third, they widely used endemic stromatolite taxa and their assemblages in stratigraphic reconstructions. In other words, researchers of the 1960s - 1970s overlooked the obvious fact that Riphean stromatolites are unsuitable for defining and correlating the above boundaries, and that they cannot serve as a tool for the general subdivision of the Riphean. This was understood later, when much attention was focused on the chronostratigraphic Precambrian boundaries (Semikhatov *et al.*, 1991; Semikhatov, 1993).

The stratigraphic usage of Riphean stromatolites was essentially restricted, when in 1980s, their complexes and assemblages were shown to be provincial (Semikhatov, 1980, 1985, 1991; Semikhatov and Serebryakov, 1983; Golovenok, 1984). The degree of their endemism is evident from the fact that among all the taxa which are known in five Middle-Late Riphean provinces of northern Eurasia and Africa, only 52% of genera and 12% of species penetrated from one province into another. An analysis of global data shows that the high degree of endemism of the Riphean and especially pre-Riphean assemblages of stromatolite species is the general rule (Semikhatov and Raaben, in press). It is also important that only a minority of the interprovincial taxa has narrow stratigraphic ranges (the erathem and lesser), but does not necessarily keep them constant in different provinces (for analysis, see Semikhatov, 1991). The problem of whether the time position of a taxon is constant or not cannot be solved by only using the data on stromatolite distribution, and calls for independent methods of correlation. Data of chemostratigraphy and isotopic geochronology (Gorokhov *et al.*, 1995a; Knoll *et al.*, 1995) show that, when we pass from one province into another, the time constraints can be changed not only for certain genera and species of stromatolites, but also for some species successions, which were once considered (Komar, 1990) as the basis for a detailed correlation of Riphean deposits. To summarize all available data, I note the following:

(1) Stromatolites are inappropriate tools for tracing and substantiating the stratigraphic boundaries of the Proterozoic. However, they provide unique characteristics to the chronostratigraphic subdivisions of the Riphean distinguished by other methods. Respectively, they individualize these subdivisions and help in their correlation (the recognition in sections). The corresponding subdivisions usually include the Lower Proterozoic (Karelian) in gross, three erathems of the Riphean, and the Vendian (Bertrand-Sarfati and Walter, 1981; Hofmann, 1987; Semikhatov, 1991; Semikhatov *et al.*, 1991), though the compilation of global data on stromatolite taxa distribution in space and time showed that in certain large regions, some informal subdivisions subordinate to the Riphean erathems, also have individual stromatolite characteristics (Krylov, 1975, 1985; Raaben, 1975, 1985; Semikhatov and Raaben, 1994, and in press).

(2) The most constraint and confident stratigraphic synthesis on the basis of stromatolite is reliable for immense provinces comparable in size with the Phanerozoic paleobiogeographic provinces. In this case, most of the available taxa characterizing one or another stratigraphic interval with their unique combinations are applicable in stratigraphy. In their vertical distribution, such assemblages were mainly under the control

of abiotic factors, among them, the eustatic fluctuations (Gebelein, 1976; Semikhatov and Serebryakov, 1983). Nevertheless, when these assemblages occur, they offer a possibility to use stromatolites to correlate deposits in reasonable detail within vast areas (e.g. Semikhatov and Serebryakov, 1983; Liang *et al.*, 1985), and to recognize regional (provincial) horizons, which have their own paleontological image and serve to detail stratigraphic scales (Raaben, 1976; Raaben and Komar, 1983; Keller and Raaben, 1989).

(3) Interprovincial correlations on a stromatolite basis are less reliable, and have a lower resolution. They must be realized using additional independent methods providing time coordinates. However, available data suggest that there are global trends of changes in the taxonomic composition and diversity of Proterozoic stromatolites, which are related to the general evolution of ecosystems of that time (Semikhatov and Raaben, 1994, and in press).

Precambrian *microfossils* represent a large group of remains of microorganisms different in morphology, biological affinity (bacteria, cyanobacteria, lower eukaryotic algae, lower fungi, protists, and others), and ecological specialization (benthos, plankton), all preserved for our study in organic-walled and mineralized (mostly silicified) forms. Many researchers believe that microfossils are very promising for Precambrian biostratigraphy (for review, see Timofeev *et al.*, 1976; Krylov *et al.*, 1989). However, a combination of such factors as the simple structures and morphological conservatism of dominant Proterozoic microorganisms, widespread processes of their postmortal degradation causing many artefacts, two forms of preservation, and the essential facial control of microbiota taxonomic composition affords many problems for using Proterozoic microfossils in stratigraphy. In addition, the classification of organic-walled microfossils was only recently refined (Yankauskas *et al.*, 1989).

Most of the silicified Proterozoic microfossils are confined to specific shallow-water (peritidal) deposits of carbonate platforms, where they are preserved in cherty concretions which originated at the earliest stages of diagenesis (Maliva *et al.*, 1989). Microfossil assemblages from these deposits show nearly complete dominance of simple filamentous and coccoidal forms, the remnants of cyanobacteria and sometimes eukaryotic one-celled algae, both lacking the evident morphological evolution during the Proterozoic in gross, and having structurally similar analogues in present assemblages of microorganisms of shallow habitats (for references, see Knoll *et al.*, 1991; Sergeev, 1992). Assemblages of this type are not only known in all three Riphean groups of the Urals and correlative deposits of many regions, but also in the Lower Proterozoic and Vendian formations (Sergeev, 1992; Schopf, 1992; Sergeev *et al.*, 1995). Because of taphonomic reasons (Petrov *et al.*, 1995), undoubtful eukaryotes of higher stratigraphic value, the dwellers of deeper paleobasin zones, are much more rare.

For a long time after Schopf (1977), an increase of extreme dimensions of such morphotypes as individual and colonial coccoidal forms, sheaths, and trichomes was considered to be the time-dependent change in the morphology of Proterozoic prokaryotes. Recently, however, Schopf (1992) stated that an extended data base rejects this conclusion concerning prokaryotes. During the Riphean, the morphological innovations in the communities under consideration were pertinent only to certain genera, and only some of them had a wide lateral distribution. These were the following forms: some representatives of nostocalean cyanobacteria of Early Riphean origin (Sergeev *et al.*, 1995); stalked cyanobacteria *Polybessurus*, which originated in the Middle Riphean and showed interregional distribution during its late erathem (Sergeev, 1992; Green *et al.*, 1989); and spiral-cylindrical *Obruchevella* known from the Upper Riphean deposits of some Eurasian regions, Greenland, and Australia (Golovenok and Belova, 1994). Still, there is the opinion (Knoll and Sergeev, 1995; Sergeev *et al.*, 1995) that taphonomic and ecological specialization of the Early and Middle Riphean resulted in some quantitative (statistical) peculiarities of silicified prokaryotic assemblages of those times (widespread fossil akinetes of hormogonian cyanobacteria). However, this feature does not repeat in the organic-walled microbiotas demonstrating akinete abundance during the Late Riphean (Yankauskas *et al.*, 1989; Petrov and Veis, 1995). In addition, it is known that sediments of three continents, which are 1.9 - 2.1 Ga in age and deposited in deeper water environments, contain the Gunflint assemblage of fossil prokaryotes unknown in the Riphean (Moore *et al.*, 1992).

Organic-walled Riphean microfossils occur in a wide spectrum of facies of siliciclastic deposits, and show significant changes in their taxonomic composition along the basin profile. These changes demonstrate the former existence of several facial-ecological groupings of microorganisms, and investigations in Siberia (Veis and Petrov, 1994a, 1994b; Petrov and Veis, 1995) revealed that two of them, the groupings of shallow water and middle depth (called the "optimal"), are the most peculiar. The impoverished assemblage of the first consists of a few conservative prokaryotic and some presumably eukaryotic representatives: the morphologically most simple acritarchs associated with colonial coccoidal and filamentous forms. In contrast, the middle depth grouping is rich and taxonomically diverse. In addition to simple wide-ranged prokaryote morphotypes and questionable eukaryotes, it includes many benthonic and planktonic eukaryotes with complex structures. It is precisely these groupings which are the most interesting from the viewpoint of stratigraphy.

Available data on the vertical distribution of organic-walled microfossils in the Riphean deposits of northern Eurasia, and less complete data on other con-

tinents (for original materials and references, see Yankauskas *et al.*, 1989; German, 1990; Veis and Vorob'eva, 1992, 1993; Veis and Petrov, 1994b; Burzin, 1994; Mendelson and Schopf, 1992; Horodyski, 1993; Butterfield *et al.*, 1994; Knoll and Sergeev, 1995), demonstrate that after time, the representative regional successions of these fossils became more diverse in a taxonomic respect and more rich in larger acritarchs and some other morphotypes. However, radically new morphotypes or abundant new genera of these fossils appeared only at a few (from one to three) stratigraphic levels of the most complete Riphean sections, and only in "optimal" facial-ecological groupings, as it is demonstrated by data from Siberia (Veis and Petrov, 1994b; Petrov and Veis, 1995).

As exemplified by both the organic-walled and some silicified assemblages, the most important innovations in the Riphean microbiotas occurred at the very beginning of the Late Riphean, about 1 Ga ago. This time is remarkable because of the essential increase of extreme dimensions of acritarchs and widespread occurrences of their acanthomorphic (genera *Trachyhystrichosphaera* and *Prolatoforma*) and other ornamented representatives. It was also the first occurrence level of new morphotypes of filamentous forms and highly differentiated remains of lower fungi and their reproductive structures. Some changes in the composition of prokaryotes are also notable at this level, and coeval diversification of eukaryotes, the green, red and chromophyte algae, was the main event in the microbiota evolution (Knoll, 1992, 1994; Mendelson and Schopf, 1992; Butterfield *et al.*, 1994; Knoll and Sergeev, 1995).

In the classical Riphean sections of northern Eurasia, the above types of microbiota are best represented in three units: the lower part of the Lakhanda Group of the Uchur–Maya region, the Derevnya Formation of the Turukhansk uplift, and (in somewhat impoverished state) the Bederysh Subformation (the fourth from the base of the basal Zilmerdak Formation) of the Upper Riphean stratotype in the southern Urals (*Stratotip* ..., 1982; Veis and Petrov, 1994b; Petrov and Veis, 1995). The great similarity of the Lakhanda, Derevnya, and Bederysh microfossil assemblages and their difference from earlier microbiotas enable the mutual correlation of these assemblages, and suggest that in its microphytological aspect, the pre-Bederysh deposits in the Urals are comparable in every aspect to the pre-Lakhanda and coeval pre-Derevnya deposits in Siberia. However, it is impossible now to use the above characteristics of microbiotas in defining the lower boundary of the Upper Riphean: this boundary is formally fixed at the base of the Zilmerdak Formation, and the pre-Bederysh portion of the latter is free of microfossils because of facial peculiarities (Maslov, 1988, 1991).

Some representative sections of the higher Upper Riphean horizons revealed a higher taxonomic diversity of ornamented acritarchs in the middle part of this erathem, where the vase-shaped protists *Melanocyrillium* also appeared about 850 Ma ago (for references, see German, 1990; Burzin, 1994; Knoll, 1992, 1994; Mendelson and Schopf, 1992). This provides a reliable perspective for the two-unit subdivision of the Upper Riphean on a microfossil basis. It is also essential that most of the Late Riphean acritarch taxa do not penetrate into the Vendian, where the lower post-Laplandian horizons contain a distinct new assemblage of complexly ornamented larger acritarchs (Burzin, 1994; Knoll, 1992, 1994).

More differentiated patterns of lateral distribution of organic-walled microfossils are typical of the part of Riphean deposits which is below the appearance level of the Bederysh, Lakhanda, Derevnya, and correlative Upper Riphean assemblages. In the Uralian stratotype of the Riphean, the pre-Karatavian (Lower-Middle Riphean) microfossil assemblages are dominated by sphaeromorphic acritarchs in the siliciclastic facies, and by simple coccoidal and filamentous forms in silicified carbonate deposits (*Stratotip* ..., 1982; Sergeev, 1992). Only the uppermost horizons of the Middle Riphean contain, in addition to the aforementioned forms, some characteristic taxa widespread in the Upper Riphean, namely the larger sphaeromorphic acritarchs, trichome fragments of oscillatorian cyanobacteria, and others (Yankauskas *et al.*, 1989).

In central Siberia, the stratigraphic interval below the Lakhanda-Derevnya assemblage displays an important microphytological change: the appearance of the Totta (the Uchur-Maya region) and coeval Bezymyannyi (the Turukhansk uplift) microbiotas. Here, in addition to the transient medium and small acritarchs associated with simple colonial coccoidal forms, narrow sheaths and trichomes, the "optimal" facial-ecological groupings contain "gigantic" acritarchs *Chuaria*, specific colonial coccoidal forms, peculiar sheaths (including their multiserial varieties), wide trichomes, branching thallomes, and others (Veis, 1988; Veis and Vorob'eva, 1993; Veis and Petrov, 1994b). These features of microbiotas including some taxa, which were considered earlier as typical of the Upper Riphean, and considerable enlargement of some coexisting morphotypes served for some investigators (e.g. Veis, 1988; Veis and Vorob'eva, 1992, 1993; Pyatiletov, 1988; Yankauskas *et al.*, 1989) as a basis for believing that these microbiotas are Late Riphean in age, and could be assigned in the Uralian stratotype to the pre-Bederysh level of the Zilmerdak Formation, where microfossils have not been recovered.

The scarce data recently available on isotopic geochronology were insufficient to completely disprove this conclusion. However, they demonstrated that the idea suggesting the Late Riphean age of the Totta-Bezymyannyi deposits, actively advocated by some researchers with other viewpoints (Khomentovsky *et al.*, 1985; Komar, 1990; Shenfil', 1991), calls for the introduction of an independent Siberian model of the Mid-

dle-Upper Riphean boundary. This model would be different from that of the type Uralian section as established according to the specific occurrence level of the microfossil assemblage in the central Siberian sections, but not to the geological level fixed in the stratotype (Semikhatov and Serebryakov, 1983; Semikhatov *et al.*, 1991).

Recent materials convincingly show that Totta-Bezymyannyi microbiotas are unsatisfactory for verifying the Late Riphean age of the host deposits. The point is that nearly all of their characteristic representatives and some other taxa (the *Stiganema*-like multiserial cell aggregates surrounded by a sheath, showing the true branching, spiral rings of *Elatera*, and others), which were known earlier only from the Lakhanda and correlative assemblages, are now distinguished in the "optimal" groupings from the Ust'-Il'ya and Kotuikan formations, Anabar massif, (Veis and Vorob'eva, 1992; Veis and Petrov, 1994b), both pre-Late Riphean, or more precisely, Early Riphean in age according to other data. These data include the following: (1) results of C-isotope chemostratigraphy (Knoll *et al.*, 1995) show that the Ust'-Il'ya and Kotuikan formations are older than the post-Bezymyannyi succession, whose age is estimated to be 1100 - 850 Ma (Gorokhov *et al.*, 1995a; Ovchinnikova *et al.*, 1995); (2) correlations, which are based upon stromatolites and litho-stratigraphic studies (Komar, 1966; Semikhatov and Serebryakov, 1983; Shenfil', 1991), suggest that these formations are even older than those deposits of the Olenek uplift, which contain glauconites with Rb-Sr isochron and K-Ar ages of 1263 ± 13 and 1287 ± 16 Ma respectively (Gorokhov *et al.*, in press); (3) the Rb-Sr isochron and K-Ar ages of glauconite from the Ust'-Il'ya Formation are 1483 ± 5 and 1459 ± 10 Ma each (Gorokhov *et al.* 1991); and (4) the Kotuikan stromatolites are assigned to the Lower Riphean complex (Komar, 1966; Krylov, 1975). It is also remarkable that the taxonomic composition of the Ust'-Il'ya and Kotuikan organic-walled microbiotas, according to Knoll and Sergeev, is comparable with that of other Mesoproterozoic (Lower-Middle Riphean) microbiotas (Sergeev *et al.*, 1995).

All of the data in gross show that at the beginning of the Riphean, the organic-walled microbiotas were somewhat diversified in composition (the appearance of some complicated sphaeromorphic acritarchs, branching thallomes, and other forms), and the extreme dimensions of acritarchs were enlarged (Veis and Semikhatov, 1989; Yankauskas *et al.*, 1989). However, most organic-walled microbiotas of the Lower Riphean demonstrate the predominance of scant and very simple acritarchs associated with colonial coccoidal and filamentous forms of very broad stratigraphic range, although in some sections they also include some taxa typical of younger deposits (Veis and Semikhatov, 1989; Veis and Vorob'eva, 1992). A simple taxonomic composition is also characteristic of many Middle Riphean microbiotas, thus leaving no chance to discriminate the Lower and Middle Riphean deposits using their microphytologic features. Only in central Siberia, the pre-Upper Riphean deposits (pre-Lakhanda levels) yielded microfossils of a wider taxonomic composition, which is reflected in the appearance of the Totta-Bezymyannyi microbiota. However, taking into account the data on the Ust'-Il'ya and Kotuikan microbiotas, this innovation should be considered as having only regional significance.

As it was shown, Precambrian microfossils were most prominently changed at the very beginning of the Late Riphean, when the wide distribution of ornamented, mostly acanthomorphic acritarchs and other morphotypes resulted in the appearance of peculiar Lakhanda, Derevnya, Bederysh, and similar microbiotas. The characteristic vertical distribution of the Upper Riphean acritarchs and vase-shaped protists occurring in some sections contribute certain microphytological features to the lower and upper parts of this erathem.

Thus far, it is difficult to use the patterns of vertical microbiota distribution in defining the boundaries between the general subdivision of the Riphean, because representative fossil assemblages of that time are known only from discrete section intervals very limited in thickness. In main Riphean successions, these intervals cover a small fraction of a percent, and are separated by incommensurably thicker deposits which are either barren because of facial (and presumably taphonomic) factors, or contain only conservative shallow-water groupings of microfossils. Thus, the most important duty of biostratigraphy in studies on the Late Precambrian microfossils is to reveal the detailed microphytological characteristics of reference sections and the middle-depth ("optimal") groupings of fossil microorganisms, which were the most dynamic members of microbial communities of the Riphean and Vendian.

METHOD OF ISOTOPIC GEOCHRONOLOGY

Within the chronostratigraphic continuum, the isotopic geochronology is not the self-orienting method to subdivide geological time into intervals and determine chronometric boundaries. Rather, it is a tool for the calibration (dating) of stratigraphic boundaries identified by other methods, and serves in the Precambrian as one of the valuable instruments of boundary correlation. It is clear that those geochronometers and isotopic-geochronological systems, which can provide direct and reliable information on the age of supracrustal successions and stratigraphic boundaries, are most important in stratigraphy. Unfortunately, datings of this type are less numerous than age determinations of intrusive and metamorphic rocks, which only show the age limits of layered deposits.

Volcanogenic zircons seem to be the most usable geochronometers in Precambrian stratigraphy, the Riphean in particular. Morphological features of these minerals distinguish them from otherwise originated zircons, and their U-Pb isotopic systems donate confi-

dent information on the age of volcanism (for review and references, see Bibikova, 1989). The high precision of U-Pb zircon dating (±0.1% in the best laboratories) enables age determinations for discrete magmatic events within narrow time intervals, thus being favorable for the accurate dating of stratigraphic boundaries (e.g. Bowring *et al.*, 1993). For individual zircon grains, the error of such age determinations does not exceed a few million years. In contrast, the Rb-Sr or Pb-Pb isochron dating of Upper Precambrian volcanic rocks sometimes provides decreased ("rejuvenated") age values because of the disturbance of relevant isotopic systems during the trivial postvolcanic or other superimposed processes (Gorokhov, 1985; Faure, 1986). Difficulties in applying the Sm-Nd isochron method for age measurements of volcanic rocks are related to the heterogeneity of the initial Nd-isotope composition in studied samples which increases the resultant age values (Faure, 1986; Bibikova *et al.*, 1990).

Provided all of the advantages of U-Pb dating of volcanogenic zircons, this method is unable to fulfill all the demands of Riphean stratigraphy, because many key sections of this age are free of volcanic rocks. In this respect, it is remarkable that Kaufman and Knoll managed to support the calibration patterns of $\delta^{13}C$ variations in the Upper Karatavian carbonate rocks with only six precise U-Pb age determinations of zircons important for the correlation of respective reference sections. Hence, sedimentary geochronometers, the globular and fine-grained phyllosilicates (minerals of the glauconite-illite group) whose ages are determinable by Rb-Sr, K-Ar, and sometimes Sm-Nd methods, are very important for Riphean and Vendian isotopic geochronology.

The Rb-Sr and K-Ar systematics of various sedimentary rocks and minerals long ago showed that whole rock samples of clayey rocks are useless for isotopic dating, because their clastic fractions (including $2M_1$ and sometimes 1M illites) inevitably contain radiogenic ^{87}Sr and ^{40}Ar inherited from provenance rocks (Clauer, 1976; *Numerical* ..., 1982; Gorokhov and Semikhatov, 1984). Hence, recent attempts to use whole rock samples of Riphean shales in isotopic dating (Vinogradov *et al.*, 1994) should be considered only as an anachronism.

Fine fractions (less than 1 - 2 μm) of clay minerals separated from unaltered rocks, namely illite fractions, are the more promising of the sedimentary geochronometers (Clauer, 1976; *Numerical* ..., 1982; Gorokhov and Semikhatov, 1984). It was thought for a while that these fractions consist of one authigenic generation of this mineral, and they were widely used for the Rb-Sr and K-Ar age determinations of sedimentary rocks occurring out of zones of anchimetamorphism and deeper alterations.

Progressing studies showed, however, that such fractions could be heterogeneous, i.e., including both the terrigenous and authigenic components of different age and formed at various stages of a rock's geological history (Gorokhov *et al.*, 1994, 1995b). Consequently, this heterogeneity distorts the age information, causing pseudochronous relations in the Rb-Sr diagrams, or resulting in weighted mean values of the K-Ar ages. The only way to obtain stratigraphically significant age determinations for clay minerals includes the following procedures: separation of several illite subfractions of a very narrow dimension range (0.2 - 0.1 μm or lesser); their detailed study by X-ray and electron microscopy methods; mutual application of K-Ar and Rb-Sr isochron techniques for genetically homogeneous samples; and supplementary utilization of geological data by interpreting the real significance of the estimated isotopic ages (Bibikova *et al.*, 1990; Gorokhov *et al.*, 1994). This approach affords the possibility to obtain confident information on the times of early diagenetic and/or regressive catagenetic stages which affected the Upper Precambrian clayey rocks. The possibilities of this approach are limited by the lability of Rb-Sr and K-Ar systems of fine-grained illites. The last remark is equally relevant for globular layered silicates of the glauconite-illite group, which were considered to be very promising in elaborating the isotopic-geochronological scale of the Riphean (*Stratigrafiya* ..., 1963; Garris *et al.*, 1964; Keller *et al.*, 1973). However, many examples of distorted K-Ar and Rb-Sr systems of these minerals demonstrating ^{87}Sr and ^{40}Ar loss during the regressive catagenesis in the circulation zone of meteoric waters (Morton and Long, 1984; Semikhatov *et al.*, 1989) resulted in a more critical understanding of the possibilities of these geochronometers.

The keen problem of the validity of glauconite geochronometers calls for seeking the criteria, which would be useful in separating minerals with disturbed ("rejuvenated") and undisturbed isotopic systems. When obtained, the concordance of K-Ar and Rb-Sr isochron ages of glauconite alone indicates that the measured values only mark a real geological event, and do not prove the safety of the initial isotopic systems of the mineral. Mineralogical criteria for the usability of glauconites for age determinations of sedimentation (early diagenesis) history, elaborated for Mesozoic and Cenozoic rocks (*Numerical* ..., 1982), are insufficient when applied to Precambrian and Cambrian samples (Ivanovskaya *et al.*, 1988; Semikhatov *et al.*, 1989; Gorokhov *et al.*, 1991). Nevertheless, repeated efforts to use the Mössbauer spectroscopy in recognizing the safety of Rb-Sr and K-Ar systems in the minerals under consideration recently terminated with success (Gorokhov *et al.*, in press). When applied to relevant spectra, the new interpretation method of Yakovleva revealed that minerals with undisturbed isotopic systems have domen structure and ordered distribution of cations in octahedral coordination, while the loss of radiogenic ^{87}Sr and ^{40}Ar is the result of iron oxidation in the circulation zone of meteoric waters (Gorokhov *et al.*, in press; Yakovleva and Gorokhov, 1995).

Recent progress in measuring the Pb-isotope composition of geological samples with very high precision extended the methodic base of Riphean geochronology. Now there is the possibility to correctly use U-Pb and Pb-Pb isochron methods in the age determinations of carbonate rocks (for review and references, see Jahn and Cuvellier, 1994; Ovchinnikova *et al.*, 1995). During the last decade, the practice of dating the Archean to Mesozoic rocks with these methods demonstrated that some analyzed carbonates do not display isochronous relations in evolutionary diagrams. In addition, some age determinations by these isochron methods were in disagreement with stratigraphic data for various reasons (Jahn and Cuvellier, 1994). Hence, the correct utilization of carbonate geochronometers is needed in the mutual studies of their U-Pb and Pb-Pb systems. These studies should be applied to the least altered samples selected on the basis of complex geochemical criteria, and the true meaning of measured isotopic ages should be interpreted using all available geological and stratigraphic information (Jahn and Cuvellier, 1994; Ovchinnikova *et al.*, 1995). In addition, I have to note that it is impossible to take into account the recent attempts (Ponomarchuk *et al.*, 1994) to use the K-Ar method for dating whole rock samples of carbonates prior to correct identification and genetic interpretation of the K-bearing phases of the rocks.

Thus, the modern isotopic geochronology of the Riphean uses the whole series of isotopic systems and geochronometers variably resisting the imposed processes. Utilizing them in combination (U-Pb dating of zircons in the first place), it is possible to obtain confident isotopic-geochronological information, which is of prime importance for both the age determination of geological events, and the telecorrelation of chronostratigraphic units and their boundaries.

CHEMOSTRATIGRAPHIC METHOD

Upper Precambrian chemostratigraphy is based on the secular variations of the C-isotope composition in carbonate rocks, and on the evolution of the Sr-isotope composition in paleooceans, which is depicted by using initial $^{87}Sr/^{86}Sr$ ratios in marine carbonates.

The isotopic fractionation during the autotrophic absorption of CO_2 and the balance of carbon masses entering in and escaping from the global ocean predetermine the fact that during every time period, the isotopic variations in the carbonate and organic carbon composition reflect the proportions between buried volumes of these two carbon phases (Hayes, 1983). Studied Phanerozoic sections revealed both the long-term trends of $\delta^{13}C$ variations in carbonates, and the short-term (not longer than a biostratigraphic zone or its part) excursions of this parameter related to certain events in the biosphere (for references, see Knoll *et al.*, 1995). However, despite the evident significance of these variations, they were rarely used in correlating Phanerozoic deposits because of the high biostratigraphic resolution within this interval.

The first efforts to reveal C-isotope records in the Precambrian were based on a limited number of samples not always strictly calibrated versus the chronometric scale, and they permitted the conclusion that $\delta^{13}C$ values are approximately constant (variations within $0 \pm 2‰$ PDB; Eichmann and Schidlowski, 1975; Schidlowski *et al.*, 1983) in all Proterozoic carbonates. The more detailed studies of Proterozoic successions essentially corrected this conclusion. It was shown that some Proterozoic intervals show more considerable variations of $\delta^{13}C$ values. Leaving aside data on the Lower Proterozoic (Karhu, 1993; Tikhomirova and Makarikhin, 1993; and others), I will now review the Riphean examples.

Known results from a number of sections in different continents demonstrate that universal, weakly negative values of $\delta^{13}C$ (from 0 to –2‰) are typical of the Lower Riphean carbonates and a number of samples characterizing the early Middle Riphean. However, at the end of the Middle Riphean and in the basal half of the Upper Riphean, this parameter was notably higher (from +1 to +3‰ with several peaks attaining +4.7‰; Pokrovski and Vinogradov, 1991; Knoll *et al.*, 1995; and other authors mentioned in these works). Data on the Turukhansk region in Siberia show that this increase is notable in deposits which are as old as 1017 ± 91 or 1035 ± 60 Ma (Pb-Pb isochron ages for 11 and 15 points respectively; Ovchinnikova *et al.*, 1994, 1995). The second half of the Late Riphean (beginning from 850 Ma) and the Vendian revealed, in general, even heavier carbon in carbonates ($\delta^{13}C$ more than 5 - 7 and sometimes 10%), although small discrete intervals within this period corresponded to $\delta^{13}C$ minima (down to 0 and even –2‰; Kaufman and Knoll, 1995; Knoll *et al.*, 1995). These minima are interpreted as related to glaciations of the African glacioera. Similar amplitudes (from –4.6 to +3.5 and even +5.4‰), but more frequent changes in the C-isotope composition of carbonates occurred during the Vendian and at the very beginning of Cambrian (Brasier *et al.*, 1994; Kaufman *et al.*, in press).

The global character, frequency of occurrences and amplitudes of $\delta^{13}C$ fluctuations are usable for telecorrelations with a high resolution, especially for the Precambrian-Cambrian boundary deposits. However, one has to take into account that the cumulative curve of C-isotope variations in the Upper Precambrian carbonates has segments different in age, but corresponding to identical, or very similar values of $\delta^{13}C$. Thus, when correlating C-isotope parameters, one must first use independent (paleontological, isotopic-geochronological) information correctly bounding at least one segment of the variation curve to the time scale, and secondly, to compare the extended sequential variations of $\delta^{13}C$ in stratigraphically complete sections. It should also be noted that age calibration of the standard $\delta^{13}C$

variation curve for the Late Precambrian is now based on the interpretation of microphytological data, some reconstructed models, and section correlations, the latter sometimes problematic.[1] Hence, the aforementioned standard curve should still be better calibrated against the time scale. Despite this, C-isotope chemostratigraphy is definitely significant for correlations, and already there are convincing examples when it was successfully used for correlating the Precambrian-Cambrian boundary deposits (Magaritz *et al.*, 1991; Brasier *et al.*, 1993, 1994; Kaufman *et al.*, in press) and older Upper Proterozoic strata (Narbonne *et al.*, 1994; Kaufman and Knoll, 1995; Knoll *et al.*, 1995).

Sr-chemostratigraphy utilizes the Sr-isotope composition in the global ocean, which is supposed to be uniform at every given moment, but varying with time in a manner depending on the changeable proportions of Sr entering the ocean, and derived either from continents with a high average $^{87}Sr/^{86}Sr$ ratio, or from mantle rocks with low values of this parameter (for review, see Faure, 1986; Gorokhov *et al.*, 1995a). For the bulk of the Phanerozoic, modern Sr-chemostratigraphy provides an age resolution corresponding to 1 Ma or lesser intervals, up to several thousand years within certain periods (DePaolo and Ingram, 1985; Smaley *et al.*, 1994). This is a result of the complex oscillatory character of $^{87}Sr/^{86}Sr$ variations in Phanerozoic oceans, which are illustrated by the curve based on approximately 1300 analyzed samples assigned to clearly identified levels of the stratigraphic scale.

For the Sr-isotope variation curve of Proterozoic oceans, the data base is much less representative. In general, this curve has an ascending character with a considerable minimum corresponding to the Early Karatavian time, the interval of 950 - 800 Ma ago (Veizer *et al.*, 1983; Asmerom *et al.*, 1991; Gorokhov *et al.*, 1995a). Its pre-Late Yurmatinian portion (older than 1100 - 1150 Ma) needs to be substantiated by more detailed studies (Pokrovski and Vinogradov, 1991; Gorokhov *et al.*, 1995a). However, the other portion comprising the terminal Middle Riphean (Yurmatinian), Late Riphean, and Vendian intervals is based upon modern, sufficiently representative (more than 260 data points), and precise isotopic measurements in several sections, and could be accepted as adequately well constrained (Derry *et al.*, 1989, 1992; Asmerom *et al.*, 1991; Kaufman *et al.*, 1993; Gorokhov *et al.*, 1995a, Kaufman *et al.*, in press).

[1] For instance, there is a widespread opinion that tillites of Massachusetts and Newfoundland resting on volcanic rocks, whose zircons yielded age values of 602 ± 3 and 606 ± 3.4 Ma (U-Pb method), are correlative with the Varangerian (Laplandian) glaciohorizon, which is basal in the Vendian, and that this glaciohorizon and related prominent negative excursions of $\delta^{13}C$ values are 610 - 590 Ma old (Harland *et al.*, 1990; Knoll and Walter, 1992; Bowring *et al.*, 1993; Kaufman and Knoll, 1995). However, available isotopic datings for the Laplandian glacial deposits in their classical region (the East European platform and the Urals) show that the horizon age is within the range of 650 ± 20 - 620 ± 15 Ma (Keller and Semikhatov, 1990; Semikhatov *et al.*, 1991).

The most remarkable features of the curve are the following: (1) the general increase of $^{87}Sr/^{86}Sr$ ratios from 0.7045 - 0.7050 to 0.7060 - 0.7062 during the Early Riphean and the greater part of the Middle Riphean; (2) the decrease of these ratios at the very end of the Middle Riphean (somewhat earlier than 1000 Ma according to Pb-Pb isochron age determinations of carbonate rocks; Ovchinnikova *et al.*, 1994, 1995), which ceased during the Early Karatavian (about 950 - 800 Ma ago), when the ratios fell down to 0.7052 - 0.7054; (3) the profoundly increasing contents of radiogenic Sr during the Late Karatavian and especially Vendian, when $^{87}Sr/^{86}Sr$ ratios rose from the last values up to 0.7085 - 0.7087 in the middle of the Nemakit-Daldynian stage, and then, at the beginning of the Tommotian time, decreased down to 0.7081 (Asmerom *et al.*, 1991; Derry *et al.*, 1992, 1994; Gorokhov *et al.*, 1995a; Kaufman *et al.*, in press).

During the Late Karatavian and Vendian, the average rate of $^{87}Sr/^{86}Sr$ ratio growth (1.3×10^4 per 10 Ma) is considerably higher than the analytical uncertainty of modern mass spectrometers used to measure the Sr-isotope composition. Thus, as was already noted (Gorokhov *et al.*, 1995a), the method of Sr-isotope chemostratigraphy would be able to provide unbelievable resolution for Precambrian stratigraphy corresponding to the level of ±5 Ma, if this portion of the calibration curve would have unidirectional and monotonous changes of $^{87}Sr/^{86}Sr$ ratios. However, the available data show that during the Late Karatavian and Vendian these changes had variable gradients, and were even negative during certain periods (Asmerom *et al.*, 1991; Kaufman *et al.*, 1993; Gorokhov *et al.*, 1995a). Consequently, in order to realize all of the potentials of Sr-isotope chemostratigraphy and obtain a higher resolution in correlating Riphean and Vendian deposits, we have to detail the standard variation curve of $^{87}Sr/^{86}Sr$ ratios and better calibrate it against the time scale. At present, this calibration is very dependent on the accepted models of interregional correlations of sections, age determinations of sedimentary geochronometers, interpretation of paleontological data, and sample age estimations on the basis of theoretical models relating the thickness and presumable accumulation interval of deposits (e.g. Asmerom *et al.*, 1991; Gorokhov *et al.*, 1995a).

Nevertheless, even data available now discriminate Sr-isotope characteristics of several sequential intervals of the Late Precambrian, such as the Late and Early Vendian, Late and Early Karatavian, terminal Yurmatinian, and to a certain extent, older Riphean subdivisions. Similar to C-isotope chemostratigraphy, the discrimination and interregional correlation of all these intervals have to be carried on by analyzing extended and continuous sections, and applying additional methods of time coordinate determination in order to recognize heterochronous section intervals with a similar Sr-isotope signature. Otherwise there is always a chance of "missing a step" and to take for correlative some similar, but heterochronous segments of both the

Sr- and C-isotope variation curves. The simultaneous processing of data of both chemostratigraphic methods is one of the real ways to avoid this obstacle, because time intervals of the most significant changes in Sr- and C-isotope compositions were discordantly specific during the Late Riphean and Vendian.

Finally, the separate problem of Precambrian chemostratigraphy is related to the necessity of sampling the least altered rocks preserving original isotopic parameters, thus usable to depict time-dependent variations of $\delta^{13}C$ and initial $^{87}Sr/^{86}Sr$ ratios. At present, there are a number of petrographic and geochemical criteria for such a selection (Asmerom *et al.*, 1991; Derry *et al.*, 1992; Kaufman and Knoll, 1995; Gorokhov *et al.*, 1995a). The obligatory application of these criteria is key in obtaining accurate data of C- and Sr-chemostratigraphy. Using it, we sometimes have to reject certain samples under study, and even certain geological bodies of regional rank, such as the Upper Riphean deposits of the Patom Highland, which experienced deep catagenetic alterations (Pokrovski and Gertsev, 1993; Gorokhov *et al.*, 1995a). The next requirement of isotopic chemostratigraphy is the close stratigraphic spacing of samples selected for investigations. This is especially important when they are selected for C-isotope measurements, because many excursions of the $\delta^{13}C$ variation curve, the significant correlation markers, are confined to very narrow section intervals not more than few meters thick (e.g., Brasier *et al.*, 1994; Knoll *et al.*, 1995; Kaufman *et al.*, in press).

To conclude this section, I note that the simultaneous processing of C- and Sr-chemostratigraphic data on the Turukhansk Riphean section and Uralian stratotype of the Riphean, in combination with U-Pb age determinations of carbonate rocks, affords a new approach in solving the problem of the Middle-Upper Riphean boundary position in the Siberian sections. This most keen and disputable problem of the Upper Precambrian stratigraphy in northern Eurasia will be considered elsewhere.

PALEOCLIMATIC METHOD

It is well known that Upper Precambrian deposits include lithologic indicators of contrasting paleoclimatic environments (evaporites, tillites, and other rocks). However, only glacial and related deposits are usable in stratigraphy, because it is precisely these sediments which form extended geological bodies with discrete positions in sections. During the past 40 - 50 years, their significance for stratigraphic correlations was treated differently due to the difficulties related to correctly recognizing past glacial deposits, and insufficient understanding of the climatic regularities of their formation (for review, see Chumakov, 1989, 1992).

Recent progress in the diagnostics of tillites and associated deposits provided the grounds for confident identification of the Upper Precambrian glacial formations in many regions of all continents except Antarctica (Chumakov, 1978, 1989, 1993; Hambrey and Harland, 1985), while the proved relations of glaciations with global cooling epochs (for review, see Chumakov, 1992) demonstrated the geological isochronism of certain glaciohorizons. These horizons represent the climatostratigraphic units comprising a lateral series of glacial and interglacial formations of comparable ages which were deposited in vast geological regions.

To judge by analogy with Phanerozoic glaciohorizons, time spans of their Upper Precambrian counterparts are estimated to be between a few m.y. and a few dozen m.y. (Chumakov, 1985). Similar intervals (10 - 20 Ma) are revealed by analyzing the duration of considerable negative excursions of $\delta^{13}C$ values related to global glacial events (Kaufman and Knoll, 1995). In their synopsis of available data, Knoll and Walter (1992) concluded that the Varangerian (Laplandian) glaciohorizon accumulated during approximately 20 Ma. Because various glaciohorizons usually comprise two or more tillite levels separated by interglacial deposits, the diachronism of their boundaries hardly exceeds 5 - 10 Ma, which is a negligible value as compared to the entire interval of the Precambrian. Formation periods of the so-called "cap dolomites" resting on glaciohorizons proper and corresponding to the deglaciation stages were presumably equal to a few thousand years, i.e., momentary from the geological viewpoint (Chumakov, 1993).

In other words, the Upper Precambrian glaciohorizons are isochronous reference horizons marking the short-term events which affected vast regions, or even more than one continent. Consequently, they demonstrate the high stratigraphic potential of the regional rank.

To use these horizons for interregional telecorrelations, one must first establish reliable age relations between more than a dozen regional glaciohorizons, which are now distinguished among the Riphean, Vendian and Vendian-Cambrian deposits of different continents (Chumakov, 1978, 1989; Hambrey and Harland, 1985). This problem could be solved only on the basis of precise isotopic-geochronological, chemostratigraphic, and paleontological data, because the glacial deposits proper do not yield any solid information on their formation time. It remains to be seen whether a deeper understanding of glaciation chronology will result in the better age discrimination of successive glaciohorizons.

Recent interregional correlations suggest that indicators of glaciations do not occur in the Lower and nearly all of the Middle Riphean deposits. The oldest Riphean tillites were distinguished in two regions near the Middle-Upper Riphean boundary (Chumakov, 1993). On the other hand, at least four glacial periods were identified higher: two in the Upper Riphean, one in the Lower Vendian, and one more near the Vendian-Cambrian boundary. Their deposits show a distribution of interregional and intercontinental ranks, and are a valuable

instrument for correlations. For instance, the Upper Riphean glacial deposits are known in equatorial and southwestern Africa, North America (the Rocky Mountains), Greenland, Australia, and presumably in Siberia (the Middle Siberian glaciohorizon; Chumakov, 1993). The Lower Vendian tillites and associated deposits are traceable in a larger area, including northwestern and eastern North America, Spitzbergen, the East European platform, Urals, and various regions of China and Australia.

However, time-ranges of respective glacial periods and the stratigraphic positions of some glaciohorizons need to be better constrained. Above, I noted the controversial opinions regarding the age of the Varangerian (Laplandian) glaciohorizon (Chumakov, 1989; Semikhatov *et al.*, 1991; Harland *et al.*, 1990; Knoll and Walter, 1992; Keller and Semikhatov, 1990). The same should be noted regarding the first Late Riphean glaciation, which is referred to the events that happened between 950 and 850 Ma ago. The real necessity to refine the age of regional glaciohorizons is clearly evident from two examples: (1) the Upper Precambrian glaciohorizons of southwestern Africa found their firm position in the stratigraphic scale only recently based on combined geological, isotopic-geochronological, and chemostratigraphic data (Kaufman *et al.*, 1991); and (2) the Jbeliat tillite of northern Africa, which was long considered as the Lower Vendian (Laplandian) according to its position in the section and paleoclimatic data, is now referred on the basis of discovered fossils to the sub-Tommotian level (Culver *et al.*, 1988; Bertrand-Sarfati *et al.*, 1995).

Thus, the wide lateral distribution of glaciohorizons, whose deposits were formed during short and discrete periods of global cooling, is a promising instrument for detailed interregional and intercontinental correlations of the Upper Riphean and Vendian deposits. However, these correlations should be preliminary supported with independent age determinations of regional depositional successions in order to avoid the confusion of different glaciation events. Without this chronological groundwork, the Upper Precambrian glaciohorizons are only useful for regional correlations.

CONCLUSION

Thus, changes in the taxonomic composition of the Late Precambrian stromatolites and microfossils, and large-scale C- and Sr-isotopic variations in carbonate rocks depict the unique paleontological and chemostratigraphic features of consecutive intervals of the Riphean and Vendian time. In addition, the isotope-geochronological data show that these intervals were decreasing in their duration.

In fact, the microfossil composition, insignificantly variable during the Early and Middle Riphean, became notably diversified not only during the entire Late Riphean and Vendian, but also during their subordinate subdivisions. Significant variations of the C-isotope composition of Upper Precambrian carbonates were initiated only during the second half of the Middle Riphean and later, during the Late Riphean and especially Vendian, they became more frequent and contrasting. Changes in the Sr-isotope composition of sea water considerably progressed in rate and amplitude only from the end of the Middle Riphean to attain the maximum gradient during the Vendian. This tendency is least evident in stromatolite evolution, although these fossils also demonstrate greater contrast in diversity during the Karatavian and Vendian than during older intervals of the Late Precambrian. In other words, the secular decrease in duration of stratigraphic subdivisions, each demonstrating specific paleontological and chemostratigraphic features, corresponds to changes in both the evolutionary rate of Precambrian bios, and the variation amplitudes of isotopic and geochemical parameters in the global paleoocean. This seems to be a reflection of the general evolutionary trend of Proterozoic ecosystems. To complete the aforesaid, I note that the taxonomic diversity and individualization degree of microfossil and stromatolite assemblages also grow upward in the section to specify the aforementioned intervals.

As it is known, in modern chronostratigraphic scales of the Precambrian, the boundary of general subdivisions are identified on the basis of geological events which affected the stratotype areas of a unit or its lower boundary. For instance, in the stratigraphic scale of the Precambrian, which was accepted for the former USSR territory in 1990, the lower boundaries of the three Riphean erathems are formally fixed at basal levels of siliciclastic members of the Burzyan, Yurmata, and Karatau groups corresponding to the initiation of new stages in the geological evolution of the stratotype region, each preceded by unconformities.

All of these members do not contain paleontological remains (disregarding some primitive acritarchs at the base of the Burzyan Group), and their composition is unsuitable for C- and Sr-chemostratigraphic studies. Hence, the isotopic-geochronological data are now of prime importance in tracing (correlating) boundaries of the chronostratigraphic subdivisions of the Riphean. Paleontological and chemostratigraphic data identify therewith the specific features of certain section intervals (subdivisions) and their correlation with the stratotypes of the Riphean erathems, or with certain portions of these stratotypes. To substantiate the erathem boundaries on the basis of this data, it is first necessary to study comprehensive paleontological (microfossils and stromatolites) and chemostratigraphic (C and Sr) characteristics of deposits adjacent to these boundaries, and then attain higher precision in correlating the pertinent sections with the Uralian stratotypes of the Lower, Middle and Upper Riphean.

Available data suggest that the Precambrian section of the Turukhansk uplift is one of the most promising

for the substantiation of the Middle-Upper Riphean boundary on a bio- and chemostratigraphic basis, while the Upper Riphean of the southern Urals and Spitsbergen represents a suitable model for elaborating the procedure of subdividing the erathems into subordinate chronostratigraphic units. Actual scientific problems concerning this model obligate the detailed study of the chemostratigraphic parameters of the Karatau Group, to carry on the isotopic dating with modern precision for its various horizons, and to detail the distribution patterns of stromatolites and microfossils in this interval on a facial-ecological basis.

Consequently, the specific bio- and chemostratigraphic features of the three Riphean erathems and some of their subordinate subdivisions afford, in combination with isotopic-geochronological and some climatostratigraphic data, not only the possibility to recognize and correlate these units in widely separated sections, but also the promising and real perspective of their definition, i.e., of identification of their lower boundaries on a paleontological and chemostratigraphic basis.

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REFERENCES

Asmerom, Y., Jacobsen, S.B., Knoll, A.H., *et al.*, Strontium Isotopic Variations of Neoproterozoic Seawater: Implications for Crustal Evolution, *Geochim. Cosmochim. Acta.*, 1991, vol. 55, no. 10, pp. 2883 - 2894.

Bertrand-Sarfati, J., Stromatolite Columnaires du Precambrian Superieur, Sahara Nord-Occidental, *C.N.R.S. Paris, Ser. Geol.*, 1972, no. 14, pp. 1 - 245.

Bertrand-Sarfati, J. and Walter, M.R., Stromatolite Biostratigraphy, *Precambrian Res.*, 1981, vol. 15, no. 3, pp. 313 - 371.

Bertrand-Sarfati, J., Moussine-Poushkine, A., Amard, B., and Ait Kaci Ahmed, A., First Ediacara Fauna Found in Western Africa and Evidence for an Early Cambrian Glaciation, *Geology*, 1995, vol. 23, no. 1, pp. 133 - 136.

Bibikova, E.V., *Uran-Svintsovaya Geokhronologiya Rannikh Etapov Razvitiya Drevnikh Shchitov* (Uranium-Lead Geochronology of Early Stages in Evolution of Ancient Shields), Moscow: Nauka, 1989.

Bibikova, E.V., Gorokhov, I.M., Neimark, L.A., and Semikhatov, M.A., Diverse Isotopic-Geochronological Systems and Geochronometers of the Precambrian, *Obshchie Voprosy Raschleneniya Dokembriya SSSR* (General Problems of Precambrian Subdivision in the USSR), Ufa: Bashk. Nauchn. Tsentr Akad. Nauk SSSR, pp. 7 - 13.

Bowring, S.A., Grotzinger, J.P., Isachsen, C.E., *et al.*, Calibration Rates of Early Cambrian Evolution, *Science*, 1993, vol. 261, no. 5126, pp. 1293 - 1298.

Brasier, M.D., Khomentovsky, V.V., and Corfield, R.M., Stable Isotope Calibration of the Earliest Skeletal Fossil Assemblages in Eastern Siberia (Precambrian-Cambrian Boundary), *Terra Nova*, 1993, vol. 5, no. 2, pp. 225 - 232.

Brasier, M.D., Rozanov, A.Yu., Zhuravlev, A.Yu., *et al.*, A Carbon Isotope Reference Scale for the Lower Cambrian Succession in Siberia: Report of IGCP Project 303, *Geol. Mag.*, 1994, vol. 131, no. 6, pp. 767 - 783.

Burzin, M.B., Principal Trends in Historical Evolution of Phytoplankton during the Late Precambrian and Early Cambrian, *Ekosistemnye Perestroiki i Evolyutsiya Biosfery* (Ecosystem Reorganizations and Biosphere Evolution), Moscow: Nedra, 1994, pp. 51 - 62.

Butterfield, N.J., Knoll, A.H., and Swett, K., Paleobiology of the Neoproterozoic Svanbergfiellet Formation, *Spitsbergen Fossil and Strata*, 1994, no. 15, pp. 1 - 84.

Chumakov, N.M., *Dokembriiskie Tillity i Tilloidy* (Precambrian Tillites and Tilloids), Moscow: Nauka, 1978.

Chumakov, N.M., Glacial Events in the Past and Their Geological Significance, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 1985, vol. 51, no. 1/4, pp. 319 - 346.

Chumakov, N.M., Glacial Horizons and Problems of the Late Precambrian Paleomagnetism, *Problemy Stratigrafii Verkhnego Proterozoya i Phanerozoya* (Problems of Upper Proterozoic and Phanerozoic Stratigraphy), Moscow: Nauka, 1989, pp. 42 - 57.

Chumakov, N.M., The Problems of Old Glaciations (Pre-Pleistocene Glaciogeology in the USSR), *Soviet Sci. Rev. Ser. G., Geology*, New York: Harwood Acad., 1992, vol. 1, part 3, pp. 1 - 208.

Chumakov, N.M., Riphean Middle Siberian Glaciohorizon, *Stratigr. Geol. Correlation*, 1993, vol. 1, no. 1, pp. 17 - 28.

Clauer, N., Geochimie Isotopique du Strontium des Mibieux Sedimentaires – Application a la Geochronologie de la Coverture du Craton Ouest-Africain, *Sci. Geol. Mem. Strasbourg*, 1976, pp. 1 - 256.

Cloud, P.E. and Semikhatov, M.A., Proterozoic Stromatolite Zonation, *Am. J. Sci.*, 1969, vol. 267, no. 11, pp. 1017 - 1061.

Cowie, J.W., Natural Boundaries in the Global Stratigraphic Time Scale of IUGS, Abstract of Papers, *28th Int. Geol. Congr.*, Washington, 1989, vol. 1, pp. 336.

Culver, S.J., Pojeta, J., and Repetski, J.S., First Record of Early Cambrian Shelly Microfossils from West Africa, *Geology*, 1988, vol. 16, no. 7, pp. 596 - 599.

DePaolo, D.J. and Ingram, B.L., High Resolution Stratigraphy with Strontium Isotopes, *Science*, 1985, vol. 227, no. 4689, pp. 938 - 941.

Derry, L.A., Keto, L.S., Jacobsen, S.B., *et al.*, Sr Isotopic Variation in Upper Proterozoic Carbonates from Svalbard and East Greenland, *Geochim. Cosmochim. Acta*, 1989, vol. 53, no. 9, pp. 2331 - 2339.

Derry, L.A., Kaufman, A.J., and Jacobsen, S.B., Sedimentary Cycling and Environmental Change in Late Proterozoic: Evidences from Stable and Radiogenic Isotopes, *Geochim. Cosmochim. Acta*, 1992, vol. 56, no. 3, pp. 1317 - 1329.

Earth's Pre-Pleistocene Glacial Record, Hambrey, M.J. and Harland, W.B., Eds., Cambridge: Cambridge Univ., 1985.

Eichmann, R. and Schidlowski, M., Isotope Fractionation between Coexisting Carbonate Pairs in Precambrian Sediments, *Geochim. Cosmochim. Acta*, 1975, vol. 39, no. 5, pp. 585 - 595.

Faure, G., *Principles of Isotope Geology*, New York: Wiley, 1986.

Garris, M.A., Kazakov, G.A., Keller, B.M., *et al.*, Geochronological Scale of the Upper Proterozoic (Riphean and Vendian), *Absolyutnyi Vozrast Geologicheskikh Formatsii* (Absolute Age of Geological Formations), Moscow: Nauka, 1964, pp. 431 - 455.

Gebelein, C.D., The Effect of the Physical, Chemical and Biological Evolution of the Earth, *Stromatolites*, Walter, M.R., Ed., Amsterdam: Elsevier, 1976, pp. 499 - 516.

German, T.N., *Organicheskii Mir Milliard Let Nazad* (Organic World a Billion Years Ago), Leningrad: Nauka, 1990.

Golovenok, V.K., Stromatolites and Microphytolites in the Precambrian Stratigraphy: A Perspective and Reality, *Sov. Geol.*, 1984, no. 8, pp. 43 - 54.

Golovenok, V.K. and Belova, M.Yu., "Gigantism" in Precambrian Microfossils and Its Biostratigraphic Significance, *Stratigr. Geol. Correlation*, 1994, vol. 2, no. 6, pp. 514 - 519.

Gorokhov, I.M., *Rubidii-Strontsievyi Metod Isotopnoi Geokhronologii* (Rubidium-Strontium Method of Isotopic Geochronology), Moscow: Energoatomisdat, 1985.

Gorokhov, I.M., Clauer, N., Turchenko, T.L., *et al.*, Rb-Sr Systematics of Vendian-Cambrian Claystones from the East European Platform: Implication for a Multistage Illite Evolution, *Chem. Geol.*, 1994, vol. 112, no. 1, pp. 71 - 89.

Gorokhov, I.M., Kutyavin, E.P., Mel'nikov, N.N., and Turchenko, T.L., Isotopic Dating of the Lower Cambrian Clays from Estonia and Their Interpretation, *Stratigr. Geol. Korrel.*, 1995b, vol. 3, no. 5, pp. 54 - 65.

Gorokhov, I.M. and Semikhatov, M.A., Rb and Sr Behavior during Processes of Sedimentary Rock Formation, Communication II: Rb and Sr Behavior during Diagenesis, Catagenesis, and Initial Metamorphism, *Litol. Polezn. Iskop.*, 1984, no. 2, pp. 86 - 109.

Gorokhov, I.M., Semikhatov, M.A., Baskakov, A.V., *et al.*, Strontium Isotopic Composition in the Riphean, Vendian, and Lower Cambrian Carbonates from Siberia, *Stratigr. Geol. Korrel.*, 1995, vol. 3, no. 1, pp. 3 - 33.

Gorokhov, I.M., Semikhatov, M.A., Drubetskoi, E.R., *et al.*, Rb-Sr and K-Ar Age of the Lower Riphean Sedimentary Geochronometers of the Anabar Massif, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1991, no. 7, pp. 17 - 32.

Gorokhov, I.M., Yakovleva, O.V., Semikhatov, M.A., and Ivanovskaya, T.A., Rb-Sr and K-Ar Age and Mössbauer Spectra of Globular Layered Silicates of Glauconite Group: The Middle Riphean Debengda Formation of the Olenek Uplift, Northern Siberia, *Litol. Polezn. Iskop.* (in press).

Green, J.W., Knoll, A.H., and Swett, K., Microfossils from Silicified Stromatolitic Carbonates of the Upper Proterozoic Limestone-Dolomite "Series," Central-East Greenland, *Geol. Mag.*, 1989, vol. 126, no. 5, pp. 567 - 585.

Grey, K. and Thorne, A.M., Biostratigraphic Significance of Stromatolites in Upward Shallowing Successions of the Early Proterozoic Duck Creek Dolomite, Western Australia, *Precambrian Res.*, 1985, vol. 29, no. 2, pp. 183 - 206.

Grotzinger, J.P., Facies and Evolution of Precambrian Carbonate Depositional Systems: Emergence of the Modern Platform Archetype, *Soc. Econ. Paleontol. and Mineral.*, 1989, Spec. Publ. 14, pp. 79 - 106.

Harland, W.B., Armstrong, R., Cox, A.V., *et al.*, *A Geological Time Scale 1989*, Cambridge: Cambridge Univ., 1990.

Hayes, J.M., Geochemical Evidence Bearing on the Origin of Aerobiosis, a Speculative Hypothesis, *Earth's Earliest Biosphaere: Its Origin and Evolution*, Schopf, J.W., Ed., Princeton: Princeton Univ., 1983, pp. 291 - 301.

Hedberg, H.D., Basis for Chronostratigraphic Classification of the Precambrian, *Precambrian Res.*, 1974, vol. 1, no. 1, pp. 165 - 177.

Hofmann, H., Precambrian Biostratigraphy, *Geosci. Can.*, 1987, vol. 14, no. 3, pp. 135 - 154.

Horodyski, R.J., Paleontology of Proterozoic Shales and Mudstones: Examples from the Belt Supergroup, Chuar Group and Pahrump Group, Western USA, *Precambrian Res.*, 1993, vol. 61, no. 2, pp. 241 - 278.

Ivanovskaya, T.A., Gorokhov, I.M., Semikhatov, M.A., *et al.*, Mineralogical and Geochemical Aspects of Using Globular Layered Silicates in Isotopic Geochronology, *Isotopnye Metody v Geologii, Geokhimii i Metallogenii* (Isotopic Methods in Geology, Geochemistry, and Metallogeny), Leningrad: Nauka, 1988, pp. 8 - 33.

Jahn B.-M. and Cuvellier, H., Pb-Pb and U-Pb Geochronology of Carbonate Rocks: an Assessment, *Chem. Geol. (Isotope Geosci. Sec.)*, 1994, vol. 115, no. 2, pp. 125 - 151.

Karhu, J.A., Paleoproterozoic Evolution of the Carbon Isotope Ratios of Sedimentary Carbonates in the Fennoscandian Shield, *Bull. Geol. Surv. Finl.*, 1993, no. 371.

Kaufman, A.J., Hayes, J.M., Knoll, A.H., and Germs, G.J.B., Isotopic Composition of Carbonates and Organic Carbon from Upper Proterozoic Succession in Namibia: Stratigraphic Variations and the Effects of Diagenesis and Metamorphism, *Precambrian Res.*, 1991, vol. 49, no. 2, pp. 301 - 327.

Kaufman, A.J., Jacobsen, S.B., and Knoll, A.H., The Vendian Record of Sr and C Isotopic Variation in Seawater: Implication for Tectonics and Paleoclimate, *Earth Planet. Sci. Lett.*, 1993, vol. 120, no. 3, pp. 409 - 430.

Kaufman, A.J. and Knoll, A.H., Neoproterozoic Variations in the Carbon Isotopic Composition of Seawater: Stratigraphic and Biochemical Implications, *Precambrian Res.*, 1995, vol. 79, no. 2, pp. 186 - 203.

Kaufman, A.J., Knoll, A.H., Semikhatov, M.A., *et al.*, Isotopic Chemostratigraphy of Proterozoic-Cambrian Boundary Beds in the Western Anabar Region, Northern Siberia, *Geol. Mag.* (in press).

Keller, B.M., *Rifeiskie Otlozheniya Kraevykh Progibov Russkoi Platformy* (Riphean Deposits in Marginal Depressions of Russian Platform), Moscow: Akad. Nauk SSSR, 1952.

Keller, B.M., Subdivisions in General Stratigraphic Scale of the Precambrian, *Dokl. Akad. Nauk SSSR*, 1966, vol. 171, no. 6, pp. 1405 - 1408.

Keller, B.M., Kazakov, G.A., Krylov, I.N., *et al.*, New Data on the Riphean (Upper Proterozoic) Stratigraphy, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1960, no. 12, pp. 26 - 41.

Keller, B.M. and Khomentovsky, V.V., The Riphean Era and Its Subdivisions, *Stratigrafiya Pozdnego Dokembriya i Kembriya* (Late Precambrian and Cambrian Stratigraphy), Moscow: Akad. Nauk SSSR, 1960, pp. 149 - 159.

Keller, B.M., Kratz, K.O., Mitrofanov, F.P., *et al.*, Information about All-Union Conference on General Problems in Subdividing the Precambrian, *Sov. Geol.*, 1977, no. 12, pp. 145 - 149.

Keller, B.M., Polevaya, N.I., and Semikhatov, M.A., Late Precambrian, *Geokhronologiya SSSR, T. 1: Dokembrii* (Geochronology of the USSR, Vol. 1: Precambrian), Leningrad: Nauka, 1973, pp. 307 - 322.

Keller, B.M. and Raaben, M.E., Horizons of the Upper Precambrian, *Problemy Stratigrafii Verkhnego Proterozoya i Fanerozoya* (Problems of the Upper Proterozoic and Phanerozoic Stratigraphy), Moscow: Nauka, 1989, pp. 6 - 12.

Keller, B.M. and Semikhatov, M.A., Reference Sections of the Riphean in Continents, *Itogi Nauki i Tekhniki: Stratigrafiya, Paleontologiya* (The Results of Science and Engineering: Stratigraphy, Paleontology), Moscow: Vses. Inst. Nauch. Tekh. Inform., 1968, pp. 5 - 108.

Keller, B.M. and Semikhatov, M.A., Isotope Geochronology for the Vendian of the USSR, *The Vendian System, Vol. 2: Regional Geology*, Sokolov, B.S. and Fedonkin, M.A., Eds., Berlin: Springer, 1990, pp. 184 - 190.

Khomentovsky, V.V., Shenfil', V.Yu., and Yakshin, M.S., The Riphean of Siberian Platform, *Geol. Geofiz.*, 1985, no. 7, pp. 25 - 33.

Knoll, A.H., The Early Evolution of Eukaryotes: A Geological Perspective, *Science*, 1992, vol. 256, pp. 622 - 627.

Knoll, A.H., Proterozoic and Early Cambrian Protists: Evidence for Accelerating Evolutionary Tempo, *Proc. Nat. Acad. Sci. USA*, 1994, vol. 91, no. 6, pp. 6743 - 6750.

Knoll, A.H. and Sergeev, V.N., Taphonomic and Evolutionary Changes across the Mesoproterozoic-Neoproterozoic Transition, *N. Jb. Geol. Palaeontol. Abh.*, 1995, vol. 195, nos. 1 - 3, pp. 289 - 302.

Knoll, A.H. and Walter, M.R., Latest Proterozoic Stratigraphy and Earth History, *Nature*, 1992, vol. 356, pp. 673 - 678.

Knoll, A.H., Swett, K., and Mark, J., Paleobiology of a Neoproterozoic Tidal Flat/Lagoonal Complex: The Draken Conglomerate Formation, Spitsbergen, *J. Paleontol.*, 1991, vol. 65, no. 4, pp. 531 - 570.

Knoll, A.H., Kaufman, A.J., and Semikhatov, M.A., The Carbon-Isotopic Composition of Proterozoic Carbonates: Riphean Successions from Northwest Siberia (Anabar Massif, Turukhansk Uplift), *Am. J. Sci.*, 1995, vol. 295, no. 7, pp. 823 - 850.

Komar, V.A., *Stromatolity Verkhnedokembriiskikh Otlozhenii Severa Sibirskoi Platformy i Ikh Stratigraficheskoe Znachenie* (Stromatolites from Upper Precambrian Deposits of Siberian Platform and Their Stratigraphic Significance), Moscow: Nauka, 1966.

Komar, V.A., Stromatolites and Correlation of Reference Riphean Sections in Siberia and Urals, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1990, no. 10, pp. 3 - 15.

Komar, V.A., Krylov, I.N., Nuzhnov, S.V., *et al.*, Three-Unit Divisibility of the Riphean Based on Stromatolites, *Geologiya Dokembriya* (Precambrian Geology), Moscow: Nedra, pp. 172 - 185.

Korolyuk, I.K., Lower Cambrian and Proterozoic Stromatolites of the Irkutsk Amphitheater, *Tr. Inst. Geokhim. Reg. Geol.*, Irkutsk, 1960, vol. 1, pp. 112 - 161.

Krylov, I.N., Riphean Evolution of Columnar Branching Stromatolites in Southern Urals, *Dokl. Akad. Nauk SSSR*, 1960, vol. 132, no. 4, pp. 895 - 898.

Krylov, I.N., *Stolbchatye Vetvyashchiesya Stromatolity Rifeiskikh Otlozhenii Yuzhnogo Urala i Ikh Znachenie dlya Stratigrafii Verkhnego Dokembriya* (Columnar Branching Stromatolites from Riphean Deposits of Southern Urals and Their Significance for the Upper Precambrian Stratigraphy), Moscow: Nauka, 1963.

Krylov, I.N., *Stromatolity Rifeya i Fanerozoya SSSR* (Riphean and Phanerozoic Stromatolites of the USSR), Moscow: Nauka, 1975.

Krylov, I.N., Stromatolites in the Upper Precambrian Stratigraphy: Problem-85, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1985, no. 11, pp. 44 - 55.

Krylov, I.N., Veis, A.F., and Sergeev, V.N., Microfossils in the Precambrian Stratigraphy: Problems and Perspectives, *Problemy Stratigrafii Verkhnego Proterozoya i Fanerozoya* (Problems of Upper Proterozoic and Phanerozoic Stratigraphy), Moscow: Nauka, 1989, pp. 31 - 42.

Liang, Yu., Zhu, Sh., Zhang, L., *et al.*, Stromatolite Assemblages of Late Precambrian in China, *Precambrian Res.*, 1985, vol. 29, nos. 1 - 3, pp. 15 - 32.

Magaritz, M., Kirschvink, J.L., Latham, A.J., *et al.*, Precambrian/Cambrian Boundary Problem: Carbon Isotope Correlation for Vendian and Tommotian Time between Siberia and Morocco, *Geology*, 1991, vol. 19, no. 8, pp. 847 - 850.

Maliva, R.G., Knoll, A.H., and Siever, R., Secular Change in Chert Distribution: A Reflection of Evolving Biological Participation in the Silica Cycle, *Palaios*, 1989, vol. 4, no. 5, pp. 519 - 532.

Maslov, A.V., *Litologiya Verkhnerifeiskikh Otlozhenii Bashkirskogo Megantiklinoriya* (Lithology of Upper Riphean Deposits in the Bashkir Mega-Anticlinorium), Moscow: Nauka, 1988.

Maslov, A.V., Sedimentary Complexes in the Riphean Sections of Southern Urals, *Litol. Polezn. Iskop.*, 1991, no. 4, pp. 66 - 82.

Mendelson, C.V., and Schopf, J.W., Proterozoic and Early Cambrian Acritarchs, *The Proterozoic Biosphere: A Multidisciplinary Study*, Cambridge: Cambridge Univ., 1992, pp. 219 - 232.

Moore, T.B., Horodyski, R.J., Lipps, J.H., and Schopf, J.W., Distinctive Problematical Proterozoic Microfossils, *The Proterozoic Biosphere: A Multidisciplinary Study*, Cambridge: Cambridge Univ., 1992, pp. 233 - 240.

Morton, J.P. and Long, L.E., Rb-Sr Ages of Glauconite Recrystallization: Dating Times of Regional Emergence above Sea Level, *J. Sediment. Petrol.*, 1984, vol. 54, no. 2, pp. 495 - 506.

Narbonne, G.M., Kaufman, A.J., and Knoll, A.H., Integrated Chemostratigraphy and Biostratigraphy of the Windermere Supergroup, Northwestern Canada: Implication for Neoproterozoic Correlations and the Early Evolution of Animals, *Bull. Geol. Soc. Am.*, 1994, vol. 106, no. 12, pp. 1281 - 1292.

Numerical Dating in Stratigraphy, Part I, Odin, G.S., Ed., New York: Wiley, 1982.

Ovchinnikova, G.V., Semikhatov, M.A., Belyatskii, B.V., *et al.*, Pb-Pb Age of Middle Riphean Carbonates from Siberia: The Sukhaya Tunguska Formation of the Turukhansk Uplift, *Dokl. Ross. Akad. Nauk*, 1994, vol. 339, no. 6, pp. 789 - 793.

Ovchinnikova, G.V., Semikhatov, M.A., Gorokhov, I.M., *et al.*, U-Pb Systematics of Precambrian Carbonates: The Riphean Sukhaya Tunguska Formation of the Turukhansk Uplift in Siberia, *Litol. Polezn. Iskop.*, 1995, no. 6, pp. 45 - 61.

Petrov, P.Yu., Semikhatov, M.A., and Sergeev, V.N., Development of the Riphean Carbonate Platform and Distribution of Silicified Microfossils: The Sukhaya Tunguska Formation of the Turukhansk Uplift in Siberia, *Stratigr. Geol. Korrel.*, 1995, vol. 3, no. 5, pp. 80 - 100.

Petrov, P.Yu. and Veis, A.F., Facial-Ecological Structure of the Derevnya Formation Microbiota: Upper Riphean of the Turukhansk Uplift in Siberia, *Stratigr. Geol. Korrel.*, 1995, vol. 3, no. 5, pp. 13 - 40.

Pokrovskii, B.G. and Gertsev, D.O., Upper Precambrian Carbonates with Anomalous Light Carbon Isotope Composition (Southern Part of Middle Siberia), *Litol. Polezn. Iskop.*, 1993, no. 1, pp. 64 - 80.

Pokrovskii, B.G. and Vinogradov, V.I., Strontium, Oxygen, and Carbon Isotopic Composition in Upper Precambrian Carbonates from Western Slope of the Anabar Massif (Kotuikan River), *Dokl. Akad. Nauk SSSR*, 1991, vol. 320, no. 5, pp. 1245 - 1250.

Ponomarchuk, V.A., Shenfil', V.Yu, Yakshin, M.S., *et al.*, Direct Dating of Stromatolites from the Olenek Uplift Using the K-Ar Method, *Dokl. Ross. Akad. Nauk*, 1994, vol. 339, no. 3, pp. 378 - 381.

Preiss, W.V., Intercontinental Correlations, *Stromatolites*, Walter, M.R., Ed., Amsterdam: Elsevier, 1976, pp. 359 - 370.

Pyatiletov, V.G., Late Precambrian Microfossils from the Uchur-Maya Region, *Pozdnii Dokembrii i Rannii Paleozoi Sibiri: Rifei i Vend* (Late Precambrian and Early Paleozoic of Siberia: Riphean and Vendian), Novosibirsk: Inst. Geol. Geofiz. Akad. Nauk SSSR, 1988, pp. 47 - 104.

Raaben, M.E., Upper Riphean Stromatolites of the Polyudov Range and Their Vertical Distribution, *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1964, vol. 39, no. 2, pp. 86 - 101.

Raaben, M.E., Columnar Stromatolites and Late Precambrian Stratigraphy, *Am. J. Sci.*, 1969, vol. 267, no. 1, pp. 1 - 18.

Raaben, M.E., *Verkhnii Rifei kak Edinitsa Obshchei Stratigraficheskoi Shkaly* (Upper Riphean as a Unit of General Stratigraphic Scale), Moscow: Nauka, 1975.

Raaben, M.E., Perspectives To Detail the Upper Precambrian Biostratigraphy, *Stratigrafiya i Sedimentologiya: Geologiya Dokembriya* (Stratigraphy and Sedimentology: Precambrian Geology), Moscow: Nauka, 1976, pp. 198 - 208.

Raaben, M.E., Lower Riphean Stromatolite Complex of India and Problems of Burzyan Phythem Stratigraphy, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1985, no. 11, pp. 35 - 43.

Raaben, M.E. and Komar, V.A., The Lower-Upper Karatavian Boundary in the Uralian Stratotype, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1983, no. 9, pp. 84 - 96.

Schatsky, N.S., Tectonic Synopsis of the Volga-Urals Region and Adjacent Western Slope of the Southern Urals, *Materialy k Poznaniyu Geologicheskogo Stroeniya SSSR, Nov. Ser., Vyp. 2(6)* [Materials for Geological Exploration of the USSR, New Ser., Issue 2(6)], Moscow: Mosk. O-vo Ispyt. Prir., 1945, pp. 1 - 110.

Schatsky, N.S., Occurrences of Terrestrial Plant Spores in Oldest Cambrian Deposits, and Geological Significance of this Discovery, *Doklady Obshchego Sobraniya AN SSSR, 10 - 13 Iyunya 1947 g.* (Proc. General Session Acad. Sci. USSR, June 10 - 13, 1947) Moscow: Akad Nauk SSSR, 1948, pp. 82 - 90.

Schatsky, N.S., Oldest Deposits in Sedimentary Cover of the Russian Platform, and Its Paleozoic Structure, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952a, no. 1, pp. 17 - 32.

Schatsky, N.S., Paleozoic-Proterozoic Boundary and Riphean Deposits of the Russian Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952b, no. 5, pp. 5 - 19.

Schatsky, N.S., Les Relations du Cambrien avec Proterozoic et les Plissement Baikaliens, *Les Relations entre Precambrian et Cambrian, Coll. Int. CNRS*, Paris, 1957, no. 76, pp. 81 - 89.

Schatsky, N.S., Principles of Late Precambrian Stratigraphy and the Riphean Interval, *Stratigrafiya Pozdnego Dokembriya* (Late Precambrian Stratigraphy), Moscow: Akad. Nauk SSSR, 1960, pp. 5 - 15.

Schatsky, N.S., The Riphean Era and Baikalian Folding, *Izbrannye Trudy, T. 1* (Selective Works, Vol. 1), Moscow: Akad. Nauk SSSR, 1963, pp. 600 - 619.

Schidlowski, M., Hayes, J.M., and Kaplan, J.R., Isotopic Inferences of Ancient Biochemistries: Carbon, Sulfur, Hydrogen and Nitrogen, *Earth's Earliest Biosphere: Its Origin and Evolution*, Schopf, J.W., Ed., Princeton: Princeton Univ., 1983, pp. 149 - 186.

Schopf, J.W., Biostratigraphic Usefulness of Stromatolitic Precambrian Microbiota: A Preliminary Analysis, *Precambrian Res.*, 1977, vol. 5, no. 1, pp. 143 - 173.

Schopf, J.W., Proterozoic Prokaryotes: Affinities, Geologic Distribution, and Evolutionary Trends, *The Proterozoic Biosphere: A Multidisciplinary Study*, Cambridge: Cambridge Univ., 1992, pp. 195 - 218.

Semikhatov, M.A., *Rifei i Nizhnii Kembrii Eniseiskogo Kryazha* (Riphean and Lower Cambrian of the Enisei Ridge), Moscow: Nauka, 1962.

Semikhatov, M.A., *Stratigrafiya i Geokhronologiya Proterozoya* (Proterozoic Stratigraphy and Geochronology), Moscow: Nauka, 1974.

Semikhatov, M.A., Experience in Stromatolite Studies in the USSR, *Stromatolites*, Walter, M.R., Ed., Amsterdam: Elsevier, 1976, pp. 337 - 358.

Semikhatov, M.A., On the Upper Precambrian Stromatolite Standard of North Eurasia, *Earth Sci. Rev.*, 1980, vol. 16, no. 2, pp. 235 - 247.

Semikhatov, M.A., Stromatolites in the Precambrian Stratigraphy: Analysis-84, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1985, no. 4, pp. 3 - 21.

Semikhatov, M.A., Present Concepts of Subdividing the Precambrian: An Analysis, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1991, no. 8, pp. 3 - 13.

Semikhatov, M.A., General Problems of Proterozoic Stratigraphy in the USSR, *Soviet Sci. Rev. Sec. G., Geology*, New York: Harwood Acad., 1991, vol. 1, part 1, pp. 1 - 192.

Semikhatov, M.A., General Subdivision of the Precambrian: Comparison of the Latest Scales, *Stratigr. Geol. Korrel.*, 1993, vol. 1, no. 1, pp. 6 - 20.

Semikhatov, M.A., Gorokhov, I.M., Kutyavin, E.P., *et al.*, Potentials of Sedimentary Geochronometers Analyzed in the Riphean Totta Formation of Eastern Siberia, *Litol. Polezn. Iskop.*, 1989, no. 6, pp. 3 - 18.

Semikhatov, M.A. and Komar, V.A., Precambrian Stromatolites: Biological Interpretation, Classification, and Stratigraphic Significance, *Problemy Stratigrafii Verkhnego Proterozoya i Fanerozoya* (Problems of Upper Proterozoic and Phanerozoic Stratigraphy), Moscow: Nauka, 1989, pp. 13 - 31.

Semikhatov, M.A. and Raaben, M.E., Dynamics of the Global Diversity of Proterozoic Stromatolites. Article I: North-

ern Eurasia, China, and India, *Stratigr. Geol. Korrel.*, 1994, vol. 2, no. 6, pp. 492 - 513.

Semikhatov, M.A. and Raaben, M.E., Dynamics of the Global Diversity of Proterozoic Stromatolites. Article II: Africa, Australia, North America, and General Synthesis, *Stratigr. Geol. Korrel.* (in press).

Semikhatov, M.A. and Serebryakov, S.N., *Sibirskii Gipostratotip Rifeya* (Siberian Hypostratotype of the Riphean), Moscow: Nauka, 1983.

Semikhatov, M.A., Shurkin, K.A., Aksenov, E.M., *et al.*, New Stratigraphic Scale for the Precambrian in the USSR, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1991, no. 4, pp. 3 - 13.

Serebryakov, S.N., *Osobennosti Formirovaniya i Razmeshcheniya Rifeiskikh Stromatolitov Sibiri* (Features of Formation and Distribution of Riphean Stromatolites in Siberia), Moscow: Nauka, 1975.

Sergeev, V.N., *Okremnelye Mikrofossilii Dokembriya i Kembriya Urala i Srednei Azii* (Precambrian and Cambrian Silicified Microfossils from Urals and Middle Asia), Moscow: Nauka, 1992.

Sergeev, V.N., Knoll, A.H., and Grotzinger, J.P., Paleobiology of the Mesoproterozoic Billyakh Group, Anabar Uplift, Siberia, *Mem. Paleontol. Soc.*, 1995, no. 39, pp. 1 - 37.

Shenfil', V.Yu., *Pozdnii Dokembrii Sibirskoi Platformy* (Late Precambrian of Siberian Platform), Novosibirsk: Nauka, 1991.

Smalley, P.C., Higgins, A.C., Howarth, R.J., *et al.*, Seawater Sr Isotope Variation through Time: A Procedure for Constructing a Reference Curve To Date and Correlate Marine Sedimentary Rocks, *Geology*, 1994, vol. 22, no. 5, pp. 431 - 434.

Sokolov, B.S., The Age of Oldest Sedimentary Cover in Russian Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952, no. 5, pp. 21 - 31.

Sokolov, B.S., The Vendian and Problems of the Precambrian-Paleozoic Boundary, *Geologiya Dokembriya* (Precambrian Geology), Moscow: Nauka, 1964, pp. 135 - 150.

Sokolov, B.S., The Vendian: Principles of Substantiation, Boundaries and Position in the Scale, *Stratigrafiya Verkhnego Proterozoya SSSR* (Upper Proterozoic Stratigraphy in the USSR), Leningrad: Nauka, 1979, pp. 42 - 61.

Stratigrafiya SSSR: Verkhnii Dokembrii (Stratigraphy of the USSR: Upper Precambrian), Keller, B.M., Ed., 1963.

Stratotip Rifeya: Paleontologiya, Paleomagnetizm (The Riphean Stratotype: Paleontology, Paleomagnetism), Keller, B.M., Ed., Moscow: Nauka, 1982.

Tikhomirova, M. and Makarikhin, V.V., Possible Reason for the ^{13}C Anomaly in Lower Proterozoic Sedimentary Carbonates, *Terra Nova*, 1993, vol. 5, no. 2, pp. 244 - 248.

Timofeev, B.V., German, T.N., and Mikhailova, N.S., *Mikrofossilii Dokembriya, Kembriya i Ordovika* (Precambrian, Cambrian, and Ordovician Microfossils), Leningrad: Nauka, 1976.

Veis, A.F., Riphean-Vendian Microfossils from the Uchur-Maya and Turukhansk Regions of Siberia, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1988, no. 5, pp. 47 - 64.

Veis, A.F. and Petrov, P.Yu., Dependence of Taxonomic Diversity of Organic-Walled Riphean Microfossils from Siberia on Their Formation Environments, *Ekosistemnye Perestroiki i Evolyutsiya Biosfery* (Ecosystem Reorganizations and Biosphere Evolution), Moscow: Nedra, 1994a, pp. 32 - 42.

Veis, A.F. and Petrov, P.Yu., The Main Peculiarities of the Environmental Distribution of Microfossils in the Riphean Basins of Siberia, *Stratigr. Geol. Korrel.*, 1994b, vol. 2, no. 5, pp. 397 - 425.

Veis, A.F. and Semikhatov, M.A., The Omakhta Microfossil Assemblage from the Lower Riphean of Siberia: Its Composition and Formation Environments, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1989, no. 5, pp. 36 - 55.

Veis, A.F. and Vorob'eva, N.G., Riphean-Vendian Microfossils from the Anabar Uplift, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1992, no. 1, pp. 114 - 130.

Veis, A.F. and Vorob'eva, N.G., Microbiotas of the Kerpyl' Group in the Riphean Hypostratotype of Siberia, *Stratigr. Geol. Korrel.*, 1993, vol. 1, no. 1, pp. 35 - 50.

Veizer, J., Compston, W., Clauer, N., and Schidlowski, M., $^{87}Sr/^{86}Sr$ in Late Proterozoic Carbonates: Evidence for a "Mantle" Event at ~900 Ma Ago, *Geochim. Cosmochim. Acta*, 1983, vol. 47, no. 2, pp. 295 - 302.

Vinogradov, V.I., Pokrovskii, B.G., Pustyl'nikov, A.M., *et al.*, Isotopic and Geochemical Peculiarities and Age of the Upper Cambrian Deposits in West Siberian Platform, *Litol. Polezn. Iskop.*, 1994, no. 4, pp. 49 - 76.

Walliser, O.H., Toward a More Critical Approach to Bioevents, *Lecture Notes in Earth Sciences, Vol. 8: Global Bioevents*, Berlin: Springer, 1986, pp. 5 - 16.

Walter, M.R., Stromatolites and Biostratigraphy of the Australian Precambrian and Cambrian, *Special Paper Paleontol. Assoc.*, 1972, vol. 11, pp. 1 - 190.

Yakovleva, O.V. and Gorokhov, I.M., ^{57}Fe Mössbauer Control of Ancient Glauconite Feasibility to Numerical Stratigraphy, *Terra Abstr. Suppl. Terra Nova*, 1995, vol. 7, no. 1, p. 327.

Yankauskas, T.V., Mikhailova, N.S., German, T.N., *et al.*, *Mikrofossilii Dokembriya SSSR* (Precambrian Microfossils of the USSR), Leningrad: Nauka, 1989.

Zhu Sh. and Chen, H., Characteristics of Paleoproterozoic Stromatolites, *China Precambrian Res.*, 1992, vol. 57, no. 1, pp. 135 - 163.

Stratigraphy and Geological Correlation, Vol. 3, No. 6, 1995, pp. 575 - 590. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 3, No. 6, 1995, pp. 51 - 67.
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The Vendian System and "Neoproterozoic-III"

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Abstract – After approval by the International Stratigraphic Commission of a new composite geochronologic scale subdividing the Proterozoic into 3 eras and 10 periods on the basis of geochronologic markers disengaged from their concrete stratigraphic carriers only, one period, the "Neoproterozoic-III," was ascertained for the Neoproterozoic era (from 1 Ga to the base of the Cambrian). This period with a basal level at 650 Ma can be considered as expressing the time of a real geological system because its upper boundary is already delineated by the limit of the era itself (Plumb, 1991; Cowie *et al.*, 1989). The Vendian System corresponds the chronometric interval established with these principles and the chronostratigraphic subdivision. The paper considers some historical aspects of this system elaboration, definition of its boundaries, subdivision, and correlation on the basis of biostratigraphy and global biospheric events. The position of the stratigraphic Precambrian-Cambrian boundary and criteria for its defining are subjected to criticism.

Key words: *Vendian System (Vendian), Sinian, Ediacarian, Yudomian, Lower Cambrian, Riphean, Upper Proterozoic, Neoproterozoic, Tommotian Stage, Lapland, Redkino, Kotlin, Rovno, Nemakit-Daldyn, and Sunnagin horizons, Russian, Siberian, and South Sinian platforms, askeletal Metazoa, small shelly fossils, sabelliditids, vendotaenids, microphytoplankton, stromatolites, Ediacara fauna, stratotype, stratigraphic boundaries*

After publication of our two-volume *Vendian System* (1985a, 1985b; 1990a, 1990b) in both Russian and English, supplemented by "Paleontology of the Vendian. Bibliography" (Ivanovsky, 1988), there is no sense to discuss the regional and paleontologic characteristics of the Vendian deposits of Eurasia in the former USSR or to repeat the notions of planetary correlation of the Vendian that were adopted then. However, the last decade was a time of vigorous renewed interest among geologists, biologists, and naturalists from various countries with regard to this period of Precambrian biosphere evolution; therefore, some historical aspects of the Vendian System elaboration should be discussed in more detail. First of all, this concerns the region in the Russian platform where the major, highly unique stratigraphic subdivision is characterized by the atypically unaltered lithology of ancient deposits bearing extremely rich faunal, floral, and bacterial assemblages. Naturally, this requires the consideration of materials from other regions, as well as the results of some other original investigations concerning deposits of a similar age and their fossils, which have been discovered at different times on different continents and interpreted in varying ways. It is also pertinent to review some general notions in light of the new knowledge. Some of my earlier ideas on the Vendian System were not justified, while others need to be supplemented and clarified.

I. SOURCES: RUSSIAN PLATFORM

It was undoubtedly a gift of fate that at the end of the 1940s I was involved in the unprecedented "Program of Deep Reference Drilling" in the Russian platform (1946 through the 1960s) and in the generalization of the materials from the most ancient sedimentary rocks of its cover. In doing so, I approached the problem of defining the Vendian by proceeding from the known to the unknown, i.e., from the oldest Lower Cambrian strata, the phenomenally fresh plastic "blue clays" of the Baltic region, to thick underlying deposits whose origin and age were yet to be deciphered. In addition, it was necessary to compile lithologic-facial and paleogeographic maps for the sedimentary cover as a whole (Sokolov, 1952, 1953, 1956, 1958, and others). Penetrated by drilling down to the crystalline basement in a vast region from the Baltic and Barents seas to the Black Sea and from Poland to the Urals and exposed along the western margin of the Russian platform (northwestern areas, Byelorussia, Volyn', and Podoliya), these deposits appeared to be represented mainly by marine clays, siltstones, and various sandstones with volcanogenic-sedimentary and glacial members in the basal part of the sequence (southeastern part of the platform). At first, they seemed to be fossil-free and were tentatively referred to either the Cambrian (traditional viewpoint of Leningrad geologists) or to Lower Paleozoic in general, and sometimes to the Ordovician and Silurian (in the Podoliya region). The first discoveries of *Sabellidites cambriensis* Yan. and *Platisolenites antiquissimus* Eichw. in the Moscow syneclise, Volyn', and Podoliya regions were of crucial importance in defining the actual age of these deposits and in their subdivision and correlation. These fossils allowed the position of the Lower Cambrian zones in the sequence to be unambiguously defined and the ref-

erence importance of the northwestern stratigraphic scheme with its two complexes, the Baltic (Lower Cambrian) and Vendian (Precambrian), to be outlined.

In the further development and elaboration of the stratigraphy of ancient deposits, these results were of great importance for dating the Lower Cambrian and Vendian microphytoplankton (acritarch assemblages), for study of vendotaenid flora (the most important for the Kotlin Horizon), and for defining the stratigraphic position of the first rare discoveries of Vendian microorganisms, such as *Beltanelloides sorichevae* Sok. (Onega Peninsula, northern Black Sea and Dniester regions), *Cyclomedusa plana* Glaessn. (Podoliya region), *Vendia sokolovi* Keller (northern European Russia), *Charnia massoni* Ford (Chesha Gulf region), and others. Thus, the position of the characteristic Ediacara assemblage of askeletal Metazoa was perfectly defined. The latter was from the Redkino Horizon, which overlies the Laplandian (or Varangerian) glaciohorizon of the Lower Vendian (Sokolov, 1972, 1976, 1984). Later, the extremely rich Ediacara assemblage of the Vendian was recorded in the sequences of the Zimnii and Letnii coasts of the White Sea, Onega Peninsula, and Dniester region of Ukraine (Fedonkin, 1981, 1983, 1987, 1992). This assemblage, no doubt, represents the most prominent biota of askeletal Metazoa in the Northern hemisphere and, probably, in the world. Its definite stratigraphic position in the almost continuous sedimentary sequence of the Russian platform and the completeness of the accompanying paleophytologic and paleoichnologic assemblages distributed throughout the Vendian and Lower Cambrian show that this biota has no analogues in marine deposits of similar facies. Only the Vendian-Cambrian carbonate (predominantly) sequence in the Siberian platform may conquer this sequence. Both of them are now well-correlated using the boundary horizon with sabelliditids.

The established completeness of the stratigraphic succession and diverse faunal and floral assemblages in the Vendian-Cambrian deposits makes the Russian platform the region most likely to be designated as the regional Lower Cambrian type or as the reference boundary, separating the Precambrian and Cambrian. As it is known, the global stratotype of this boundary was recently voted by the working group experts of the International Stratigraphic Commission to be located in Newfoundland (Narbonne, 1987; Brasier *et al.*, 1994; and others), but the approval of this choice was not unanimous. One of the reasons for the discrepancies in viewpoints was the fact that for the first time in biostratigraphy, the global boundary stratotype of such a high rank was not established as a result of the study of historical changes in faunal evolution, but rather, was formally selected within a certain succession of life-activity traces of unknown organisms-detritovores *Harlaniella podolica* Sok. and *Phycodes pedum* Seil. Thus, the trace fossils unexpectedly acquired the role of the "golden spike." For many years, I was a member of this group of experts, and at different times, visited the best sequences in England, Canada, Australia, China, Siberia, European Russia, Ukraine, and even in France, Spain, and North Africa, all presumably suitable for the selection of the Precambrian-Cambrian boundary standard. In 1972, I had the opportunity to also become acquainted with the sequences of the Upper Cambrian (the Conception Group with Ediacara fauna) and Cambrian in Newfoundland. However, one could not imagine then that the selection of the phantome boundary would crown the efforts of many experts and a great deal of observations on all continents. Such a boundary, probably, affords some convenience as far as it concerns specific paleoichnologic successions, but it does not meet one of the principal requirements of stratigraphy "to transfer maximum correlative functions" from one group of organisms to another (Sokolov, 1974a), or the principle of "chronologic interchangeability of features" (Meyen, 1989), which is the basis of planetary stratigraphy in general.

Surely, Russian researchers share the blame for inadequate interest of the above-mentioned group of experts in the Vendian-Cambrian succession in the Russian platform. By the end of the 1950s, the scientific interests of many researchers had already shifted to the Riphean carbonate sequences in the Urals, and then to those of Siberia, in particular, to the excellent Cambrian carbonate sequences in the Siberian platform and its southern fold framing. It was there that the classical stratigraphic scheme of the Lower Cambrian was eventually elaborated, which was acknowledged worldwide (*Yarusnoe* ..., 1983, 1984). The application of the paleontological method to the study of the marine Riphean and Cambrian deposits became the principal approach. First, stromatolites and microphytolites were investigated, followed by the study of archaeocyates and trilobites, which, owing to the works of A.G. Vologdin and E.V. Lermontova in the 1930 - 1940s, yielded excellent results. Later, particularly in connection with defining the Tommotian Stage at the base of the Cambrian (Rozanov *et al.*, 1969), small shelly fossils (SSF, according to the modern abbreviation) were subjected to these studies. From the biostratigraphical point of view, marine carbonate deposits were considered to have a decisive advantage in comparison to the Vendian-Cambrian terrigenous complexes of the Russian platform. When the Yudoma complex of the Siberian platform was established to represent a carbonate equivalent of the Vendian in the Russian platform, the solution of the problem of the Lower Cambrian boundary, i.e., the Precambrian-Cambrian boundary, automatically shifted to Siberia. In doing so, most Siberian researchers equated the Yudoma complex to the Vendian of the Russian platform, although they considered it not as an independent unit, but as the IV, uppermost subdivision of the Riphean (*Reshenie* ..., 1962). This resolution was very important for the adherents of Riphean or Upper Precambrian "stromatolite biostratigraphy" because in this case, the stromatolite succession of the

Riphean-type section in the Urals was extended upward using the distant correlations, with the Siberian sequences (Sokolov, 1978), because in the Riphean sequence type in the Urals, the IV subdivision, i.e., the Asha Formation, lacked the carbonate layers with the stromatolites and microphytolites of the "Yudoma complex." The latter was recorded only in older Riphean strata, in the Uk Formation of the Karatau Group which resulted in the appearance of a short-lived concept of the "terminal Riphean" or sinthetic Vendomian (Keller, 1973). Originally, this new subdivision was named the Vendian System (Protosystem) by Keller (1966), with an age interval of 700 - 550 Ma that approximates the modern Sinian System *s. str.* of southern China. In so doing, Keller wrote, that "stromatolites along with other problematic fossil remains of vegetative origin and isotopic datings can have practical significance in defining the Vendian" (p. 1408). With this unexpected conclusion, the researcher had redirected his focus from the marine, to the terrigenous Vendian complexes of the Russian platform. However, only with the paleontologic justification of the Vendian upper boundary as the Precambrian one and the correlation of the Vendian with the Asha Formation of the Urals was the pre-Vendian first scientifically substantiated,i.e., Precambrian age of the Riphean Group proper in its three-membered type section adopted now (Burzyanian, Yurmatinian, and Karatavian phytems or eratems). However, the shift in the scientific interest of most researchers to the study the Riphean and Vendian mainly carbonate sequences in Siberia became a reality, and therefore the problem of the Precambrian-Cambrian boundary had to be solved, as was already noted, in the sequences of the Yudoma and Variegated formations and their analogues of a new facies type, all previously referred, in general, to the Lower Cambrian. In this sense, the analogy with the initial interpretation of the Lower Cambrian volume in the Baltic shield depressions should never be considered incidental: in both cases, we are dealing with the oldest structurally indivisible sedimentary cover of platforms, usually called "Precambrian platforms." In fact, they are mostly pre-Vendian and even pre-Sinian in age (in the sense of the Sinian System of the South China platform) as I had initially thought (Sokolov, 1958). Still, binding the Vendian with the Sinian System in its Chinese meaning (Grabau, 1922; and others), I mistakenly included the former into the Paleozoic as an equivalent of the Cambrian System (Sokolov, 1952), and many researchers followed in this mistake (Khomentovskii, 1976; and others).

II. THE SIBERIAN PLATFORM

The study of the Upper Precambrian and Lower Cambrian essentially carbonate sequences in the Siberian platform resulted in many remarkable discoveries in the paleontology and biostratigraphy of the Vendian-Cambrian boundary deposits, which attracted worldwide attention, provoked a great deal of publications, and created a new sphere for further investigations (for instance, of various groups of small skeletal shelly organisms) and fruitful discussions. While the attempt to substitute the Vendian with the Yudoma Complex in the Upper Precambrian general stratigraphic scheme failed, the boundary layers between the Yudoma Formation and Variegated Beds of the Lower Cambrian essentially narrowed the limits of the potential interval, where the most satisfactory Precambrian-Cambrian boundary could be recorded. Since 1973, investigations by international teams of experts became routine (*Putevoditel'* ..., 1973; Cowie and Rozanov, 1974; Sokolov, 1974a; Cowie, 1981; Rozanov and Sokolov, 1982; Astashkin *et al.*, 1991). Of a great importance were the investigations by Rozanov and his colleagues, who discriminated the Tommotian Stage and defined its boundaries (Rozanov, 1967, 1976; Rozanov *et al.*, 1969). The base of the distinguished Sunnagin Horizon or the *Aldanocyathus* (=*Nochoroicyathus*) *sunnaginicus* Zone was thought to represent the lower boundary of the Cambrian System because this level conforms with the paleontological principle of typization of stratigraphic boundaries. This conclusion acquired worldwide popularity, although, unlike the Atdabanian Stage, recognition of the Tommotian Stage in many distribution regions of the Cambrian strata has immediately run into more or less significant difficulties.

However, for many years the Siberian platform attracted the attention of experts as the region with the most favorable paleontological, sedimentological, and geochemical characteristics of the boundary strata between the Yudoma and Variegated formations proposed for the selection of the Precambrian-Cambrian boundary stratotype, i.e., the boundary between the Vendian and Cambrian systems. Several reference sequences studied in detail in the valleys of the Aldan and Lena rivers were suggested to be appropriate for this purpose. Their analogues were the excellent sequences in the Olenek uplift, Anabar massiff slopes, and northwestern part of the platform.

The most significant event in the study of the Lower Cambrian and Upper Vendian in the Siberian platform is related to the discovery in pre-trilobite and pre-archaeocyate strata bearing diverse small shelly, tubular, and skleritomorph (according to its remains) fauna whose nature is still far from being understood. The new *Anabarites* genus appeared to be its most important component (Missarzhevskii, cited in Rozanov *et al.*, 1969). I was the first to find these small tubular-spiny forms with the carbonate-phosphate shell as far back as 1956 during field work in the Anabar massiff southern slope (Kengeede River), where they occurred in the terrigenous-carbonate member. These deposits, which were later referred to the Nemakit-Daldyn Horizon (Savitskii, 1962, 1975), rest upon the Staraya Rechka stromatolitic dolomites (future Yudoma Complex). The leading role in the study of this new small shelly fauna (SSF) from the Vendian-Tommotian

boundary strata belongs to Missarzhevskii (1969, 1989, and others), Val'kov (1975, 1982, 1987, and others), and other researchers, whose longstanding investigations provoked a series of discoveries and many publications in China, Great Britain, Canada, the USA, and Sweden. As a result, they provided an additional possibility to search the Precambrian-Cambrian boundary using the transitional forms of these small shelly organisms. The studies gave rise to new notions of: (1) the "complete *Aldanocyathus sunnanginicus* Zone" within the Lower Cambrian; and (2) the Nemakit-Daldyn (Manykai) Horizon or Stage, which preceded the Tommotian Stage. One group of researchers included this horizon, as the supplementary one, into the Lower Cambrian, whereas others considered it to represent the terminal Vendian subdivision. Khomentovskii (1976), who became an orthodox adherent of the latter viewpoint, considered the base of the *Aldanocyathus sunnaginicus* Zone, which coincided with the Tommotian Stage lower boundary, to represent "the only distinct synchronous stratigraphic level in the entire succession of Vendian-Cambrian deposits" (Khomentovskii and Karlova, 1992). It is my understanding (Rozanov and Sokolov, 1980; Sokolov, 1974) that the notion of "the complete *Aldanocyathus sunnaginicus* Zone" means a certain completeness of the Sunnagin Horizon, which, in a paleontological sense, incorporated transitional representatives of the SSF assemblage and probable archaeocyathids, and not the literally exact coincidence of the *Aldanocyathus sunnaginicus* occurrence level with the base of the Tommotian Stage, which should be excluded owing to the established facial zonality in different Early Cambrian settings of the Siberian platform (Savitskii, 1972; Khomentovskii, 1976). In this sense, the Precambrian-Cambrian boundary stratotype, which was suggested by the experts (1973) in the Ulakhan-Sulugur and neighboring sequences in the Aldan region, and later refined in the same stratotype region, as well as in the Vendian-Tommotian sequence of the Kessyusa Formation in the Olenek uplift, have many more significant advantages in their biostratigraphic correlation potential than the selected stratotype in Newfoundland. In this highly marginal sequence, the preference was given to coprolites of the enigmatic *Phycoides pedum* Seil. For tired experts, it would be better not to solve the problem of the Precambrian-Cambrian boundary at all than to solve it in this way.

Some comments concerning the type standardization procedure of boundaries between geological systems should be added to the aforesaid. These remarks are a result of my personal practice in various stratigraphic expert groups (e.g., Precambrian-Cambrian, Ordovician-Silurian, and Silurian-Devonian boundaries; stage units of these systems). First, when defining the Phanerozoic stratigraphic boundaries (it should be noted that the Cambrian System lower boundary represents the Phanerozoic boundary, even *sensu stricto*), one must strictly follow "the biological principle" of its substantiation adopted at the IGC session in Montreal (in 1972), i.e., to use only the well-studied groups of marine fauna (they are commonly called "archistratigraphic" groups), and not their traces or other auxiliary features of biological origin (for instance, the biosedimentological ones). Second, the basal biostratigraphic zone [for example, the *Aldanocyathus (Nochoroicyathus) sunnaginicus* Zone] must contain other faunal assemblages, which in other regions and sequences of the transitional facies type, could perform the transferring functions in correlation. It was this specific proposition, which resulted after 12 years (1960 - 1972) of work by experts on the Silurian-Devonian boundary, that led to the appearance of the IGCP independent project on ecostratigraphy. This project offered the possibility of defining the equivalents of the initially selected stratotype (holostratotype), i.e., peculiar transstratotypes transferring functions of the holostratotype in remote regions. Third, the principle of the "golden spike" suggests that the boundary between the contiguous geological systems only represent the boundary between the contiguous zones of these systems, which by no means always complies with the hierarchical (rank) nature of the boundary to be defined (for instance, the Vendian-Cambrian boundary represents simultaneously that between the Proterozoic and Phanerozoic or Paleozoic). Evidently, this principle should be developed into a comprehensive concept, which would take into account the boundaries of ecosystem reorganizations. Fourth, new methods of studies of the stratotype boundary, primarily defined by the biological (paleontological) method, such as the isotopic, chemostratigraphic, and magnetostratigraphic limitations, while undoubtedly important are, on their own, only somewhat autonomous in a global sense (Knoll and Walter, 1992; Narbonne *et al.*, 1994) and can still play an auxiliary role, because only biostratigraphy can control one or another level in chronostratigraphic correlation. However, in basin stratigraphy, all of these methods are of great importance, and their role will increase in future. Fifth, the international expert groups who will select the globally important stratigraphic boundary stratotype should act on the basis of consensus rather than voting. The latter contradicts the very essence of science and does not meet the requirements of scientific practice (for instance, of geological mapping).

III. THE NEMAKIT-DALDYN (MANYKAI) AND ROVNO HORIZONS

Two important consequences resulted from establishing the Cambrian lower boundary in Siberia at the base of the Sunnagin Horizon which contains, in addition to the oldest archaeocyathids, the "Sunnagin" assemblage of small shelly fauna, which appeared earlier; both are of principal significance. First, this provided an opportunity to get rid of the obsession to correlate the system lower boundary with the first occurrence level of skeletal organisms, as it appeared to be diachronous. Second, it became possible to define more

precisely the statute of a new, undoubtedly independent stratigraphic horizon, previously named the Nemakit-Daldyn or Manykai Horizon, with its own paleontologic characteristic definitely related to the *Anabarites trisulcatus* but not the *Aldanocyathus sunnaginicus* Zone. Some researchers considered this unit as a peculiar pre-Tommotian subdivision of the Lower Cambrian and included it into the Aldanian Stage (Savitskii, 1975), or correlated with the Sunnagin Horizon (Zhuravleva, 1975). Others referred the unit to the upper Yudomian as the terminal Riphean (Missarzhevskii and Rozanov, 1975) or to the Vendian, considering the latter as the Paleozoic system (Khomentovskii, 1975). All of these viewpoints are from one book (*Analogi* ..., 1975). My knowledge of the paleontologic characteristic of this horizon (besides anabaritids) dates back to 1965, when I studied sabelliditids from the lower part of the Platonovka Formation at the Sukhaya Tunguska River (the Turukhansk margin of the Siberian platform). I then continued my investigations in the Olenek uplift until 1981, when a similar sabelliditid assemblage (*Sabellidites cambriensis, Paleolina evenkiensis*, and others) was found in the lower Kessyusa Formation, which, in general, is paleontologically well-characterized (Sokolov, 1965, 1967, 1968, 1972, 1973; Sokolov and Fedonkin, 1984; *Vendskaya* ..., 1990). Still earlier, in 1956 in Irkutsk, I first determined *Sabellidites* ex gr. *cambriensis* Yan. in samples collected by Irkutsk oil-prospecting geologists from the upper Moty Formation (=Irkutsk Horizon). This species, which is the most characteristic representative of fauna from the Lower Cambrian basal strata in the Baltic region, indicated the Early Cambrian age of the Moty Formation according to the views of that time.

Later, the age of all paleontological finds was revised and referred to the Vendian (Sokolov, 1975; Sokolov and Khomentovskii, 1980), despite the stability of former views on their Early Cambrian age. The discovery of sabelliditids in Siberia was important, as it instigated a new, quite unexpected direction in the correlation of Vendian-Cambrian deposits in the Siberian and Russian platforms. In the latter platform and along its western margin (the entire Baltoscandia, Moscow-Mezen' syneclise, Volyn' region, Moldavia, Dniester region of Ukraine, and Poland), sabelliditids were discovered in many localities, where their mass occurrences were confined to a narrow interval correlative with the lower part of blue clays in the Baltic region, i.e., with basal strata of the Baltic Group (Complex). Znosko (1961) erroneously correlated this member with the *Holmia* Zone in Scandinavia, but I, myself, was also mistaken in referring the whole member of blue clays in the Russian platform to the new Baltic Stage of the Lower Cambrian, which comprised all strata up to the base of the *Volborthella tenuis-Holmia* (*Schmidtiellus*) *mickwitzi* zones (Sokolov, 1965). In Poland, the Klimontovian Stage (Aren' and Lendzion, 1974), comprising two horizons or the *Sabellidites-Platisolenites* and *Mobergella* zones, was thought to be a synonym of this sub-*Holmia* unit. Lendzion (1983) correctly recognized a significant paleogeographic reorganization in the Early Cambrian basins at the boundary between these zones.

The most significant biostratigraphic revision of this part of the sequence was performed by V.V. Kir'yanov, who widely used the results of both his own microphytologic studies and those by N.A. Volkova and others. In the northwestern Volyn' region, he justified the division of the lower Baltic Group into the Rovno Beds with *Sabellidites cambriensis* Yan., *Serpulites*(?), i.e., *Yanichevskiites petropolitanus* (Yan.), and other forms, and Stokhod Beds with *Platisolenites antiquissimus* Eich. and very rare sabelliditids (Kir'yanov, 1967, 1968, 1969). The Rovno Horizon acquired the role of the reference basal horizon of the Baltic Group throughout the Russian platform. Similarly, a definite stratigraphic position was acquired by the overlying Lontova Horizon in Estonia (Mens, 1981), which comprised the Stokhod Beds in the Podoliya region and the Mazowec Beds in Poland, i.e., all Lower Cambrian deposits underlying the *Mobergella* Zone (*Stratigrafiya* ..., 1979).

As can be seen, neither the trilobites nor archaeocyathes, which are the most important fossil groups for Cambrian stratigraphy, could be used for defining the stratotype of the Cambrian lower boundary. This role was taken over by the older group of small shelly fossils (SSF). This group is evidently heterogeneous in both its origin and composition, undoubtedly includes a series of taxa of a very high rank, bears no direct indications of its closeness with classical Ediacara biota of the Vendian, and represents a special interest for studies of biomineralization and development of the oldest invertebrates with mineral skeleton forms (siliceous, phosphatic, and carbonate). As was already mentioned, the biostratigraphic significance of SSF was revealed when studying the Vendian-Cambrian succession of carbonate deposits in the Siberian platform and another regions. Still, it appeared to be negligible for the relevant age interval in the Russian platform. As for the Lontova Horizon, only the following fossils can be considered as typical: rare *Aldanella kunda* (Öpik), undetermined forms of *Hyolithellus* genus, *Yanichevskyites* (*Serpulites*?) *petropolitana* (Yan.), some scleritomorphic aggregates, and more common *Platosolenites antiquissimus* Eichw. and *P. lontowa* Öpik, which are absent in the Siberian assemblage. However, the underlying Rovno Horizon is enriched everywhere with sabelliditids, particularly in such genera as *Sabellidites, Sokoloviina, Paleolina*, and *Saarina*. In this respect, the difference between the latter and the Nemakyt-Daldyn Horizon of Siberia concerns only some qualitative proportions of certain genera: for instance, *Paleolina* dominates in the Nemakyt-Daldyn Horizon, whereas *Sokoloviina* dominates in the Rovno Horizon, with both genera probably composing the vicariation group. However, the independent investigations and priority given to the SSF assemblage in Siberia resulted in a

stratigraphic paradox: the Nemakyt-Daldyn Horizon became regarded by most researchers as the pre-Sunnaginian, i.e., the Precambrian (Vendian, Yudomian), whereas the Rovno Horizon (with its regional analogues in European Russia, Baltic region, Ukraine, Moldavia, Poland, and Romania, everywhere including the *Sabellidites* Zone) was referred to the base of the Baltic Group, i.e., the base of the Lower Cambrian (e.g. Patrulius and Iordan, 1974; and others). As far back as 1965, before the stratigraphic nomenclature used here was introduced into practice, I conceived that it was necessary to propose a relevant correlation of the Siberian and European sequences within the interval of the Lower Cambrian, and from 1971 to 1974, I directly correlated the Nemakyt-Daldyn and Rovno horizons, including both into the Vendian as the uppermost subdivision of the latter (Sokolov, 1965, 1971, 1974b). An important argument in favor of this correlation was the discovery in the Rovno Horizon of the Podoliya region (Ternava River) of the last representatives of Ediacarian *Kullingia* and other "medusoid" forms of the Vendian, which were later studied by Gureev (1987): *Beltanelloides simplex* (Palij), *Cyclomedusa minuta* Fed., and *Kullingia concentrica* Glaessn. This point of view was formulated in final form in the *Vendskaya Sistema* ... (1985, 1990), although some geologists in Estonia and Poland continue to consider the Rovno Horizon as a unit of the Lower Cambrian.

While investigating the sabelliditids from various localities, I united them into a separate taxon Sabelliditida of a high rank (probably, of a class rank) and put forward the hypothesis that they represent the remains of the oldest pogonophors, which was backed by outstanding zoologists such as A.V. Ivanov and L.A. Zenkevich. In stratigraphic literature, sabelliditids, since Yanichevsyi's work (1939), are usually referred to the sedentary "worms," namely the lugworms, which are accepted by some researchers as true pogonophors. The very old age of sabelliditids does not rule out my hypothesis at all. The ultramicrostructural studies of sabelliditid tubes (Urbanek, 1979; Ivantsov, 1989) neither confirmed nor refuted it, but revealed their specific character. These forms can not be related to such fossils as anabaritids, hyolithids, hyolithelmints, or platisoleniits. The only common feature is the tubelike sheaths; however, the sabelliditid genera differ in their unusual length, elasticity, and mostly organic composition (*Calyptrina* and *Saarina* from the Redkino Horizon) with a varying level of chitinization (*Paleolina, Sokoloviina,* and *Sabellidites* from the Rovno and Nemakyt-Daldyn horizons). In the first case, they are well-preserved owing to film pyritization. The complete absence of sheath mineralization in sabelliditids precludes their affinity with the SSF group, while the organic and chitinoid composition of sheaths most likely relates them with the Vendian askeletal Metazoa which also originally lacked the mineralized sheaths. The paleontologic history of sabelliditids terminated at the level of the Rovno and Nemakyt-Daldyn horizons, whereas its initiation probably corresponds to the Early Vendian or Latest Riphean.

IV. PRINCIPAL PECULIARITIES OF MAIN VENDIAN SUBDIVISIONS

All of the above-listed data and discussion were aimed eventually to substantiate paleozoologic approaches for defining the Vendian-Cambrian boundary as a terminal Proterozoic system. The particular attention paid to the Rovno and Nemakyt-Daldyn horizons was predetermined by solving this problem, because in biostratigraphic respect, this chronostratigraphic level is of principal importance, as it affords the possibility to apply the paleontologic method, which is typical of the Phanerozoic stratigraphy (Sepkoski, 1978). For most of us this is a *modus vivendi*, yet, using this method, some researchers favor the base of the Rovno Horizon of the Baltic Group (*Sabellidites cambriensis* Zone) to be the lower boundary of the Cambrian System (Mens and Pirrus, 1986). Others refer to the Vendian even the Lontova Horizon, thus rising the Vendian up to a higher level of the base of the *Mobergella* Zone, which would correspond to the classical lower boundary of the Cambrian in Baltoscandia. The adherents of the New Foundland stratotype have a different point of view (Landing, 1994), which is to be expected. In the case of the Nemakit Daldyn Horizon, there was an attempt to use date on the isotope chemostratigraphy to cast doubts on the idea that the *Anabarites trisulcatus* Zone is of the Vendian (Yudomian) age. However, these data can only be accepted as regional, which is far from being of global significance, and incapable of substituting biostratotype and biostratigraphic correlation (Brasier *et al.*, 1994; Knoll and Walter, 1992).

At the same time, the Kotlin (=Kanilov) and Redkino horizons, underlying the Rovno Horizon in the Russian platform, are universally considered to represent the principal Vendian units with the most typical features of the Vendian biota. It was often mentioned in literature that the position of the enigmatic fauna of askeletal Metazoa, which is widely known under the name Ediacara fauna, became clearly defined only when the Vendian was discriminated in the general stratigraphic scale, and the chronological succession of its horizons was established between the stratotype upper boundary of the Riphean (Karatavian, 650 ± 20 Ma), or the present-day "upper boundary" of the Cryogenian (650 Ma) newly created in the Precambrian time scale, and the base of the Cambrian System. Previously termed as the oldest fauna and later dated as the Early Cambrian or even younger in the works of Australian, German, English, Russian, and Ukrainian researchers who studied sporadic finds in different continents, it was finally referred to the Upper Precambrian between 1958 and 1959 (Ford, 1958; Glaessner, 1959, 1984; and others). However, even after that, this fauna was perceived to be merely a regional phenomenon not related

to any strictly defined interval of the undivisible Proterozoic. It was not until 1970 - 1980s that the Vendian became widely used as a unit for the remote and intercontinental correlations of deposits with fossils of the Ediacara type (Glaessner, 1971; Sokolov, 1972 - 1985; Webby, 1973; Pflug, 1974; Sepkoski, 1983; Brasier, 1985; Chen Junynan, 1988; Hofmann *et al.*, 1990; Fedonkin, 1992; and many others).

In the Vendian of the Russian platform, the Ediacara fauna of askeletal Metazoa represents the most peculiar biota of the Redkino Horizon and its regional equivalents: the Ust' Pinega and Mogilev Podolskii groups in the White Sea and Podoliya regions, respectively. This fauna is diverse, abundant and well-studied now (Fedonkin, 1981, 1983, 1987 and others). The discovery of the Ediacara fauna in the Vendian of the Olenek uplift in the Siberian platform approximately at the same stratigraphic level (Khatyspyt Formation of the Khorbusuonka Group of the Yudomian) further strengthened the reference significance of this level with the askeletal fossils for correlation of the Vendian deposits (Sokolov and Fedonkin, 1984). In all probability, this level is stable on the planetary scale; it is easily and adequately distinguishable in both terrigenous and terrigenous-carbonate facies, but more sporadic in the carbonate sequences. In the biostratigraphical respect, this level is rather uniform over great distances. In those areas where tillites or tilloids occur at the base of the Vendian or its analogues, this level is either clearly postglacial or incorporated into transgressive facies, as it is observed in the Siberian platform (Cloud and Glaessner, 1982; Sokolov and Fedonkin, 1984; *Vendskaya Sistema* ..., 1985). The greatest glacial epoch (pre-Vendian and, probably, Early Vendian), the eustatic sea level rise, and the explosive expansion of askeletal Metazoa are thought to be interrelated in the biosphere evolution. However, this general empiric concept, which seems to be reliable in its basic features, undoubtedly needs further development to answer many important questions. Among the issues that need to be addressed are the following: (1) the roots of Ediacara type Metazoa (undoubtedly, the Riphean ones), (2) the remarkable stability of some Cyclozoa known from both the intertillite deposits (*"Betallenoides," Nimbia,* and *Vendella*) and Rovno Horizon, where they occur together with sabelliditids, (3) the extinct envelopes of often giant (metric!) forms of *"Vendobionta"* or *"Vendiata"* (as they are sometimes called now), and (4) the feeding mode of these organisms (presumably osmotic, because no forms with oral foramen were found). Finally, what is the actual nature of the Cloudinidae and Redkiniidae forms that occupy a peculiar position at the same stratigraphic level (Hahn and Pflug, 1985; Sokolov, 1985)?

It is well known now that the Metazoa of Ediacara type represented only a part of the Vendian biota. Simultaneously, there existed benthic and planktonic vendotaenid flora, and extremely diversified microplankton so far indivisible into zoo- and phytoforms; the existence of actinomices and various cyanellae is also undoubtedly proven. Quite peculiar biota was represented by detritovores of an indefinite taxonomic position, which imprinted the traces of their movement and feeding. We should better understand the critical epoch in the existence of many askeletal Metazoa taxa at the Redkino-Kotlin boundary, when the Ediacara biota almost completely disappeared (or was somewhere displaced) and representatives of the new algal class Vendophyceae reached an exceptional rate of growth (*Vendotenidy* ..., 1988). Answering these and many other questions related to the existence of the unexpectedly diversified Vendian biota will undoubtedly have important stratigraphic consequences.

The Kotlin Horizon and its regional equivalents, such as the Kanilov Group in the Podoliya region, the Povarovo Group in the Moscow syneclise, and the upper part of the Valdai Group in the northwestern Russian platform (from the Godov to Voronka Formation) represent perhaps the most characteristic part of the Vendian in European Russia, the Baltic region, Belarus, and the Moldavian-Ukrainian Dniester region. Formerly, the horizon comprised the so-called Laminarites Formation with the sapropelic films erroneously determined to be brown algae *"Laminarites antiquissimus"* Eichw. To avoid confusion, I gave the unit a new name, the Kotlin Formation (Sokolov, 1958; Myannil', 1958), which was adopted in practice. The Kotlin basin deposits are represented by laminated clays, claystones, siltstones, and sandstones of variable composition and green-grey to variegated in color. As compared with the typical Redkino deposits, the latter show some evidence of freshening and cold-water environments in the basin that is probably related to the second Vendian short-term glacial (Chumakov, 1992). The Kotlin biota essentially changed: all askeletal Metazoa groups became extinct; the phytoplankton diversity decreased, whereas traces of benthic organisms and detritovores became abundant. The ichnotaxons were mainly identical to those in the Redkino Horizon. *Harlaniella podolica* was the only specific benthic inhabitant. This species is absent in the Rovno Horizon (the *Sabellidites* Zone), where the first occurrence of the *Phycodes pedum* Seil. is recorded among abundant sabelliditids: *Sabellidites cambriensis, Sokoloviina costata,* and others, which are completely absent in the Kotlin (Kanilov) Horizon. This fact should be emphasized, because the finds of *Sabellidites* fragments in the "Laminarites Beds" were erroneously mentioned in a number of old geological publications.

The main constituent of the Kotlin Horizon biota is vendotaenid algae, which have a wide distribution, and are particularly well studied in the ecological and taphonomic respects in the Kanilov Group sequences in the Dniester region (Korenchuk and Ishchenko, 1980, 1981). The appearance of these oldest multicellular thallophyte aqueous plants was undoubtedly in the Riphean, but their blossoming occurred in the Vendian. Relatively rare *Eoholynia, Kalusina,* and *Serebrina* are

known from the Redkino Horizon. In the Kotlin Horizon, they are replaced by mass accumulations of *Vendotaenia* ribbons, which form separate layers composed of nonmineralized thallomes. The thallomes preserve the primary elasticity, cellular structure, sporangia, and the colonies of actinomyces of the *Primoflagella* genus and other microorganisms settled on them. The upper Kotlin Horizon contains the representatives of the *Aataenia, Thyrasotaenia* (also forming extensive accumulations of ribbons), *Kanilovia* and other genera. The Rovno Horizon is the appearance level of *Dvinia* forms (Gnilovskaya, 1971; *Vendotenidy* ..., 1988), which became completely extinct in the Lontovian time.

In the taxonomic diversity, all Vendian microfossil groups exceed various unicellular microfossils and fillamentous cyanellae of the elongated or spiral form such as *Volyniella* (=?*Grypania*) (Aseeva, 1974), with a perfectly preserved organic-walled sheath. The decades of agiotage interest in the study of these organisms created much confusion in their taxonomy and nomenclature, which is known from literature. However, the revision of innumerable new taxa that was initiated in recent years resulted in the delineation of definite groups and assemblages which opens a possibility to outline main tendencies in the phytoplankton evolution during the Late Precambrian and Early Cambrian (Burzin, 1994; and others).

Although the Kotlin Horizon takes a definite position in the Vendian of the Russian platform, the ecological and biogeographic peculiarities of its biota create certain difficulties in correlating it with the coeval horizons of the Yudomian in Siberia and the Upper Sinian in South China. In addition, biostratigraphic analogues of this horizon are absent in the Ediacara System of Australia (M. Glaessner, written communication of February 4, 1983, also reflecting P. Cloud's point of view). At the same time, remains of the vendotaenid flora, in particular of characteristic genera such as *Vendotaenia* and *Tyrasotaenia* are abundant in Siberia, China, and, less frequent in Western Europe in the deposits related to normal marine environments. I have found their abundant remains in the Yudomian Complex of the Olenek uplift, where they form separate layers, and on the slopes of the Anabar massiff. They are wide spread in the Platonovka Formation in the Enisei region of the Siberian platform and in the Yudomian of the Irkutsk amphitheater. Numerous finds of the *Vendotaenia* and *Tyrasotaenia* forms are also reported from the upper part of the Sinian System of China (Dendying Stage or Formation); however, they are insufficiently studied here and sometimes identified under the uncertain name *"Laminarites antiquissimus"* (The Sinian System, 1976; Sin Yu-sheng and Liu Kui-chih, 1976; Xing Yucheng *et al.*, 1982).

The notion of the "Sinian System" experienced numerous complicated transformations: first from the system (1922) to suberathem (1975 - 1976), which was then subdivided into a series of new systems, and finally, to the new Sinian System of southern China. The stratigraphic range of the latter is not settled yet: a part of the Dendying Formation corresponds to the Meishucun Stage of the Lower Cambrian, whereas the lower tillite-bearing formations represent only fragments of a longer stage, which preceded the accumulation of the Doushantuo Formation. As early as 1959, I hypothesized in Beijing (All-China Stratigraphic Meeting) that only this regionally remote and stratigraphically "undefined" part of the southern Sinian corresponds to the Vendian of the Russian platform. The new, recently proposed correlation scheme of the Sinian subdivisions in the Yangtze platform (Wang and Zhang, 1984), according to which the post-Riphean Vendian comprises the Nantuo, Doushantuo, and Dendying formations, is, from my point of view, close to the aforesaid idea. Still, this does not eliminate the difficulties in correlating the main Vendian subdivisions of the Russian platform with the aforementioned formations (or stages, as they are classified now by Chinese researchers). First, the Precambrian-Cambrian boundary within the upper Dendying Formation needs to be precisely defined, followed by a comprehensive study of sabelliditids, which occur practically throughout the Sinian sequence. Second, the vendotaenid flora, in particular, its specific assemblages from the Redkino and Kotlin horizons, similarly deserve detailed investigations. It seems that the stratigraphically most important sabelliditid and vendotaenid assemblages are related to the upper part of the Dendying Formation (Xing Yusheng, 1984; Xing Yusheng *et al.*, 1984). However, the peculiar forms of *Sinosabellidites* are reported along with other annelidomorphs from the deposits with an age of 740 Ma (Lower Sinian) (Sun Weiguo *et al.*, 1986). Third, there is a chance that the new assemblage of Metazoa of the Ediacara type (medusoids and *Paracharnia*) discovered in the middle Dendying Formation could be younger than the Redkino one, which already corresponds to the Kotlin level. Although deposits of the latter level lack the Ediacara fauna in both Russia and Australia, it can theoretically be found there (Sun Weiguo, 1986). Fourth, the paleontologic characteristic of the Doushantuo Formation, except for the coccoid microfossils (Zhan, 1985), is still insufficient for the correct correlation of this formation. Fifth, more complete and precise data on the paleontologic characteristic of interglacial deposits (Siedlecka and Roberts, 1992; Hofmann *et al.*, 1990) are desirable, and this concerns not only southern China, but also northern Norway and northwestern Canada. It might appear that the Protoarenicolida and Cyclozoa discovered in these deposits are the oldest Vendian or Late Riphean representatives of the benthic and pelagic Metazoa (Chen Junyuan, 1988; Hofmann *et al.*, 1990), although relevant chronometric data need further verification.

V. LAPLANDIAN (VARANGERIAN) HORIZON AND VENDIAN LOWER BOUNDARY

In Russian literature, the deposits of the Redkino and Kotlin horizons are often united under the common name Valdai Complex (sometimes Superhorizon). This term is not synonymous with the Vendian, as it was formerly considered, however the name is widely used in Precambrian stratigraphy even as a homonym of the Valdai Superhorizon of the Quaternary. The complex unites horizons which sharply differ in sedimentation history and biotas, although acritarchs, vendotaenids, and paleoichnofossils are their common constituents. Still, most important is the fact that these deposits, whose thickness in the Russian platform is measured in many hundreds of meters, are entirely postglacial. The cooling at the Riphean-Vendian boundary was a separate epoch in the glacial era of the earth's history named by Chumakov the African glacial era. He considers this era to be the Early Vendian and unites the related deposits (tillites, tilloids, marine-glacial sediments, and poorly sorted products of bedrock destruction) into the Laplandian Horizon, whose analogues are well-correlated throughout northern Europe, the Urals, China, Australia, Canada, and Africa (Chumakov, 1974, 1987, 1992). In the Russian platform, the Laplandian Horizon is well recovered by boreholes in the Volyn'-Orsha, Pachelma, and Ladoga depressions. It has a complicated structure, contains more than one tillite level, and is closely related to the marine deposits of the overlying Redkino Horizon and its age analogues, which contain the first diverse fauna of the askeletal Metazoa. Their rare finds were discussed above.

I have always believed the deposits of the melting glacier and advancing marine transgression to be, a in historical-geological sense, closely interrelated, and therefore considered the Laplandian Horizon in such regional types as the Vil'chany and Volyn' groups in Belarus, and the Volyn' and Pachelma regions to represent the basal horizon of the Vendian System. This point of view was shared by Byelorussian and Ukrainian researchers (Bessonova and Chumakov, 1969; Makhnach *et al.*, 1970, 1976). With such a content, the Vendian System was adopted in North European studies and became a part of the general scale of main stratigraphic subdivisions (system-period) of the Upper Precambrian (Harland, 1993; Harland *et al.*, 1989).

When defining the Vendian lower boundary, some researchers still focus their attention on the appearance level of askeletal Metazoa of the Ediacara type. I believe that this approach is as hopeless as defining the Cambrian System lower boundary by the appearance of skeletal invertebrates. First, skeletal organisms were already reported from the Redkino (Ediacara) Horizon of the middle Vendian. They are represented by *Cloudina* from the Nama Group in Namibia (Germs, 1972; and others), whereas the oldest "medusoid" Cyclozoa were discovered in the intertillite deposits of the Windermire Supergroup (Vendian) in the Mackenzie Mts. in Canada, i.e., in much older deposits as compared to the Ediacara Horizon (Hofmann *et al.*, 1990). However, it would be a great error to search every area of the glaciohorizon at the Vendian System base, as none of the geological systems have planetary uniform basal deposits. This is especially true for the Vendian System, which is characterized at the transition from the Riphean by major climatic, tectonic, and ecosystem reorganizations. The Early Vendian transgression in many regions of the Russian platform (the Moscow syneclise included), which spread over a territory of about 100 000 km^2, with the tillite-bearing Vil'chany-Volyn' deposits to the left behind the Redkino Horizon deposits resting directly upon the basement rocks.

The transgressive Yudoma Complex (the Yudomian) of the Siberian platform has a similar relationship with the older Riphean deposits and basement rocks overlying them over vast areas without any evidence of tillite-bearing deposits at the base; however, tillites may be present in deeper parts of the platform periphery. The Upper Sinian of southern China, which is an equivalent of the Yudomian, rests, as in the Russian platform, directly upon the crystalline basement without tillite-bearing horizons, although the latter (the Nantuo formation) occurs in their classical form in some other areas (for instance, the Yangtze River basin and Dabashan). The structural position of the Sinian cover was clearly shown by the geological mapping in China (Holland, 1989 and others). Based on indirect evidence, some Russian and Chinese researchers believe that in those cases when the transgressive Yudomian or Sinian cover lacks the basal glaciohorizon, both these subdivisions exceed in age the Vendian interval typical of the Russian platform. However, the concept of the glacioeustatic determination of the Vendian System lower boundary, suggested by myself, favors an opposite conclusion, and in this respect I share the views of those researchers who, when reasoning the Vendian age of the Manykai (Nemakit-Daldyn) Stage, consider the Yudomian to represent an incomplete equivalent of the Vendian (Matthews and Missarzhevsky, 1975). The doubtful radioisotopic measurements (700 Ma), rather than paleontologic facts, are taken for a decisive argument to support the older level of the Doushantuo Formation base as compared to that of the Vendian lower boundary in the Russian platform. Far more reliably proven is the concept, according to which only the Laplandian Horizon and Nantuo tillite formation occupy the same level (Wang and Zhang, 1984) and represent the phenomena of the planetary rank. This level marks the termination of the long and multistep Late Proterozoic glacial era, which occurred during the terminal Rephean and earliest Vendian.

This was the most critical point in the earth's history, and was associated with intense lithospheric and climatic dynamics, biotic crises, and postcrisis restorations. We documented only limited data on the Early Vendian biota, which would be useful in reconstructing

the environment and life during the relatively stable periods of this epoch. Therefore, it is vital to study the most complete Vendian sequences and the Ripheon-Vendian "transitional" deposits. Of primary concern, in this respect, are, of course, the Uralian sections (the Serebryanka Group) and the entire Arctic region inside the Polar Circle.

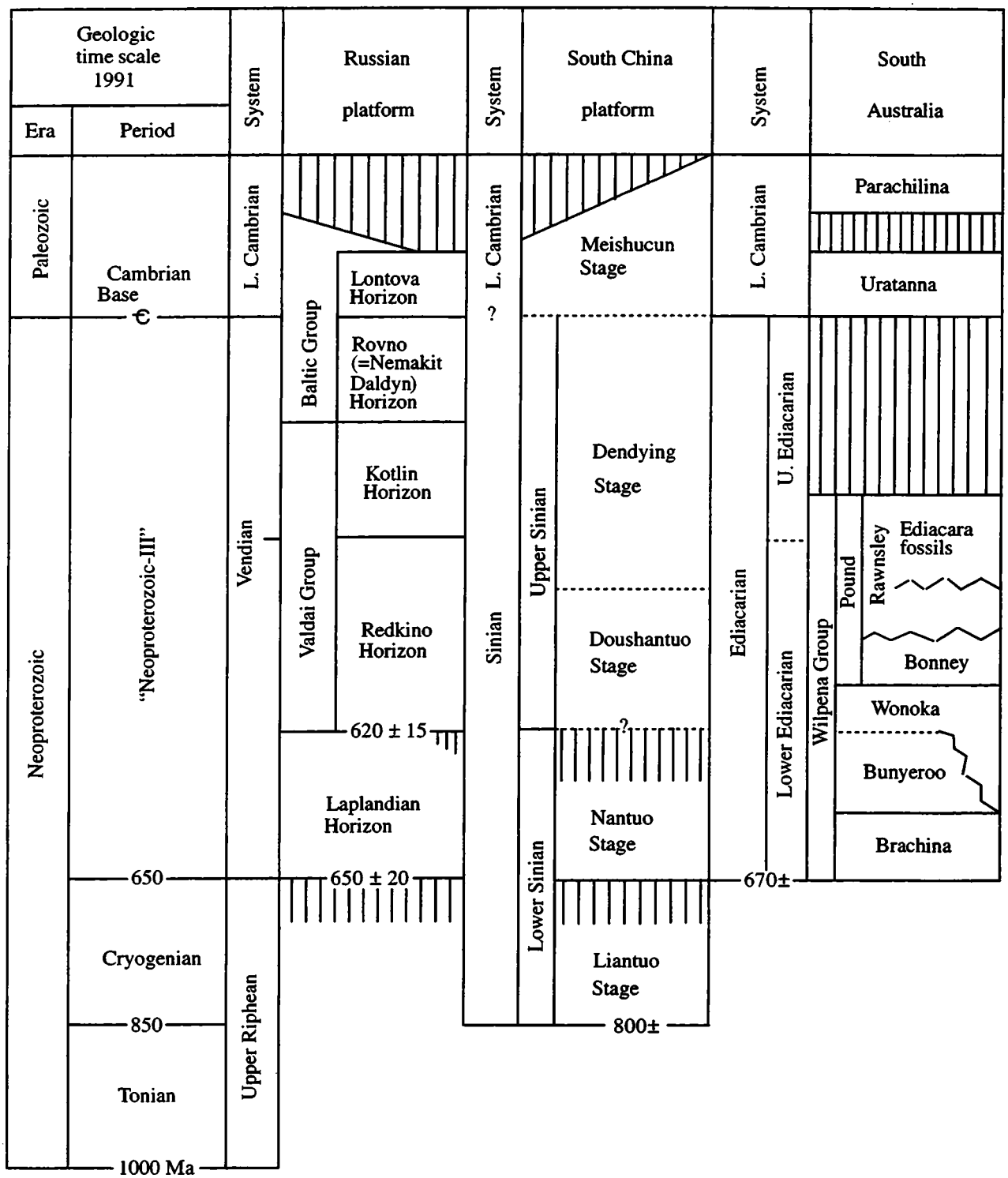
VI. THE POSITION OF THE VENDIAN IN GENERAL STRATIGRAPHIC SCALE OF THE PROTEROZOIC

Based on the foregoing, some generalizations can be made regarding the Precambrian terminal system, the only subdivision of such rank so far distinguishable in the entire sequence below the Cambrian lower boundary. This boundary is perceived in our minds as the boundary between the eons of evident (Phanerozoic) and obscure (Cryptozoic) life, respectively. Chadwick's concept (1930), originally not very popular, received wide recognition 20 years later, when the National Center of Scientific Research, France, launched a wide discussion of the problem of the transitional infra-Cambrian formations (*Les relations ...*, 1958), which attracted particular attention because of their uncertain stratigraphic position and the possibility to fill an intriguing gap in geological records. Recently, the importance of this boundary was once again discredited because of the transitional character of the biota near the Cryptozoic-Phanerozoic boundary. However, the problem of the Precambrian sedimentary formations bearing various traces of past biological systems and high-rank taxa, which experienced deep diversification, is still provoking interest.

There are two ways to express the geological time (the most concrete notion in natural history) for the classical Phanerozoic and Precambrian: the chronometric and chronostratigraphic. The first is based on isotopic data, whereas the second utilizes the physical carriers of so-called relative geological time, i.e., the successions of deposits and direct sources of chronological information: biological (paleontologic), geochemical (radioactive elements), and geophysical (paleomagnetism) data recorded in them. The first way, as was already noted, precludes the practical usage of any natural standards, but it can provide many abstract "time scales," from the standard scales measured in years (for instance, the intervals of 10 - 100 Ma) to any model scale approximately relating age dates to the boundaries of conditional subdivisions having their own nomenclature (for instance, the Cryogenian, Tonian, and others). The second way is always related to the concrete stratigraphic sequences which operate in geologic correlations with stratotypes of the subdivision and their boundaries (limitotypes), but not with scattered isotopic datings. Only this approach can provide an approximation with maximum accuracy of the planetary chronostratigraphic correlation.

It was already noted that thus far, the International Subcommission on Precambrian Stratigraphy only utilizes the purely chronometric approach to calibrate the geologic time scale (Plumb, 1991), leaving stratigraphers only the upper, pre-Cambrian third of the Neoproterozoic, the latter term characterized by Grabau (1922) as "the uncertain and misleading term." The Subcommission decided to place the lower boundary of this part of the scale ("Neoproterozoic-III") at the level of 650 Ma and to take the base of the Cambrian System for its upper chronostratigraphic limit. It was shown that only this base can serve as a starting level in attributing the chronostratigraphic meaning to the geological time interval determined by this method. Naturally, certain deviations are unavoidable in geological practice because we consider the geological system as the chronostratigraphic subdivision whose age limits cannot be defined beforehand; the procedures in stratigraphy follow the opposite order. Provided the adopted viewpoint on the upper boundary of the Precambrian terminal system, physically established or accepted in a such quality, only three systems (and, accordingly, periods) appear to be competitive: the Vendian, Ediacarian, and Sinian *s. str.* (the scheme). The first of them was discussed in detail in this paper and earlier monographs (*Vendskaya Sistema ...*, 1985a, 1985b; *The Vendian System ...*, 1990a, 1990b). Originally (1949 - 1952), the system was defined according to its content as the subdivision adequate to the Lower Cambrian, which was considered by some researchers to represent an independent system (Schatsky, 1952; and others). In this rank, it was repeatedly defined (Keller and Sokolov, 1962) and adopted by the Stratigraphic Committee of the USSR in a series of resolutions, including the general stratigraphic scheme adopted in 1991 (Glebovitskii and Shemyakin, 1994; Semikhatov, 1994) as the only Precambrian system above the Riphean. The base of the Laplandian Horizon, considered as the base of the Vendian System, has an age of 650 ± 20 Ma. Semikhatov believes this age to be more valid than the complicatedly derived values of 610 - 590 Ma ascribed to the age of the Varangerian (? – B.S.) glaciation (Bowring *et al.*, 1993). However, the evolution of Ediacara and Cambrian faunas has already been interpreted on the basis of the last conclusion (Conway, 1993).

The notion of the Ediacarian System and Period as the initial period of the Phanerozoic, but not Proterozoic eon, became extensively used after the publication of the well-known article by Cloud and Glaessner (1982). Initially, this term was used by Termier and Termier, (1960) to designate the "premier étage paleontologique," however Cloud (1970) classified the latter as the system. Jenkins (1981) discriminated the relevant deposits of Australia as a unit of the same rank, although with different stratigraphic range and the name "Ediacaran." In all three instances, the famous fauna from Ediacara, characteristic of the middle part of the Pound Sandstones, represented the key feature of this stratigraphic subdivision. Later, this member in the Flinders Range was further subdivided and correlated



Scheme of relationships between the Vendian, Sinian, and Ediacarian systems with the geologic time scale of the Neoproterozoic.

with the lower Arumbera Sandstones in the Amadeus Basin. However, in the stratotype area, a gap remained between deposits with the askeletal Metazoa and Lower Cambrian strata, which rest upon older rocks above the uneven contact, because the latters were in places deeply eroded. As it was already noted, deposits corresponding to the Upper Vendian of the Russian platform have not been recorded in the Australian sequences even though these sequence are perfectly exposed. Nevertheless, the Ediacarian is tentatively subdivided into two units: the Lower Ediacarian, to which the Ediacara fauna is mostly confined (in this

respect, it is close to the Lower Vendian in my view), and Upper Ediacarian, comprising a large hiatus which has thus far been insufficiently studied. The isotope datings for the Ediacarian are close to those for the Vendian: (650 ± 550 Ma); but they are also tentative. The entire complex of Ediacarian rocks is younger than the tillite-bearing deposits of the Late Proterozoic.

The recent analysis (1975 - 1976) of the comparative data concerning the Sinian System of South China is listed above. In many publications, the system is considered as the upper subdivision of the Sinian Suberatem, i.e., as the Upper Precambrian approximating in its stratigraphic range to the Riphean Group in the initial definition of Schatsky (1945). Still, another popular standpoint suggests including the Sinian into the Phanerozoic. The Sinian System is also subdivided into the Lower and Upper Sinian, the latter and the upper part of the former corresponding to the Vendian. In general, such a correlation seems reliable, because it is based on the main groups of common fossils characteristic of both systems; namely on askeletal Metazoa (although considerably less diverse in China), vendotaenid flora, some acritarch groups, and paleoichnologic fossils. Nevertheless, correlation of their respective stages meets certain difficulties because of insufficient knowledge of fauna and flora including abundant new taxa of generic and species rank, and also due to the different distribution of fossils throughout the sequence.

The correlation of the Sinian-Lower Cambrian and Vendian-Lower Cambrian boundaries is substantiated without any principal contradictions, whereas the lower boundaries of the Sinian and Vendian systems are essentially different: the Sinian, in fact, incorporates the Vendian. To overcome this contradiction, Harland and his colleagues eventually formulated in a series of publications the following scheme:

			(540 ± 10)
			570 ± 20 Ma
Sinian Era	Vendian Period	Ediacara Epoch	
		Varanger Epoch	
			610 ± 20 Ma
	Sturtian Period		
			800 Ma

If the base of the Sinian is dated using the basal rocks of the Sinian sedimentary cover rather than the products of basement destruction, then, taking into account its great duration, the Sinian should be considered a geological era. From the tectonic viewpoint, some researchers (Menner and Shtreis, 1971) already were of similar opinion with respect to the rank of the Vendian. In Harland's scheme, the Vendian Period occupies a more definite position corresponding to the Vendian System in the Russian platform, although new isotopic datings of the boundaries require further discussion. Still, it is difficult to agree that the name "Ediacara Epoch" can be applied to the entire upper subdivision of the Vendian. In this respect, the schemes proposed by Cloud, Glaessner and myself seem concordant with the results of comparative paleontologic studies and the real stratigraphic position of the Ediacara fauna in the middle part of the Vendian above the Laplandian Glaciohorizon.

As is seen, all three candidates for the terminal system preceding the Cambrian, which could occupy the place designated as "Neoproterozoic-III" in the geological time scale, are of sharply different volumes, differently subdivided, and characterized by contradictory isotopic datings of their own boundaries and the boundaries of their internal subdivisions. All of them contain diverse and, very often, abundant paleontologic remains. Based on this feature, their exclusion from the Cryptozic is without a doubt, factually and logically justified. However, some researchers argued for their inclusion into the Phanerozoic or, even narrower, into the Paleozoic. Before the 1960s, I also shared this view on the Vendian System position. Yet, the data presented at the Novosibirsk Symposium (first) on the paleontologic characteristics of the Precambrian and Early Cambrian (*Vsesoyuznyi Simpozium* ..., 1965) and consequent paramount success in Precambrian paleontological research compelled me to take a fresh look at both the exceptional peculiarity of the Vendian biota, and the so-called Cambrian population outburst. While this metaphorical characteristic fits the biota of the Early Cambrian invertebrates, the askeletal Metazoa of the Ediacara type were not responsible for this outburst. The higher taxa of Vendian biota are very peculiar, and cessation of their further development is perceived as a specific event in the organic evolution, which, in fact, terminated some of the processes which commenced slightly earlier. The Cambrian fauna had its own independent roots, which are to be looked for in the biota of the Late Proterozoic microorganisms and, probably, in the Vendian benthos, so far undiscovered.

Many researchers in different countries are now concerned with the choice of the Proterozoic terminal system stratotype, which would fit the geological time interval "prepared" for it. This approach is, in general, unprecedented for stratigraphy and scientifically meaningless. None of the existing geological systems, which have been established in Europe since the 1920s and studied for almost two centuries, had, has, nor will have a stratotype of such a high rank in the stratigraphic hierarchy. This can be exemplified by any geological system from the Cambrian to Quaternary. As an illustration, let us consider the Devonian System: its name was born in Great Britain (1839); the stratotypic subdivision into stages was elaborated as the result of long-standing investigations on the territory of Germany and Belgium; and the stratotype of the system's lower boundary was chosen in Czechoslovakia only in 1972. It is now obvious that a similar approach is also unavoidable in the case of the Precambrian terminal system. I can recommend only one thing: that the stratotype of subdivisions and their boundaries should be as close to the stratotype region as possible. As for the Vendian System, the territory of Russia and adjacent western countries, with their complete and well-studied

sequences in two ancient platforms and their fold framing, seems to be the most appropriate region for further domestic and international investigations.

REFERENCES

Adventures in Earth History, Cloud, P., Ed., San Francisco, 1970.

Aren', P. and Lendzion, K., Distribution and Stratigraphy of the Klimontovian Stage of the Lower Cambrian in the Platform of Poland, *Biostratigrafiya i Paleontologiya Nizhnego Kembriya Evropy i Severnoi Azii* (Biostratigraphy and Paleontology of the Lower Cambrian in Europe and North Asia), Moscow: Nauka, 1974, pp. 30 - 35.

Aseeva, E.A., On Spiral- and Ringlike Forms from the Upper Precambrian Deposits of the Podoliya Region, *Paleontol. Sb.*, 1974, no. 11, vol. 2, pp. 95 - 99.

Astashkin, V.A., Pegel', T.V., Repina, L.N., *et al.*, *Cambrian System of the Siberian Platform, Correlation Chart and Explanatory Notes,* Herndon-Trondheim: I.U.G.S., 1991, no. 27.

Bessonova, V.Ya. and Chumakov, N.M., Upper Precambrian Glacial Deposits of the Western USSR, *Litol. Polezn. Iskop.*, 1969, no. 2, pp. 73 - 89.

Bowring, S.A., Grotzinger, J.P., Isacksen, C.E., *et al.*, Calibrating Rates of Early Cambrian Evolution, *Science*, 1993, vol. 261, no. 5126, pp. 1293 - 1298.

Brasier, M.D., Evolutionary and Geological Events Across the Precambrian-Cambrian Boundary, *Geol. Today*, 1985, Sept. - Oct., pp. 141 - 146.

Brasier, M., Cowie, J., and Taylor, M., Decision on the Precambrian-Cambrian Boundary Stratotype, *Episodes*, 1994, vol. 17, nos. 1 - 2, pp. 3 - 8.

Brasier, M.D., Corfield, R.M., Derry, L.A., Rozanov, A.Yu., and Zhuravlev, A.Yu., Multiple $\delta^{13}C$ Excursions Spanning the Cambrian Explosion to the Botomian Crisis in Siberia, *Geology,* 1994, vol. 22, no. 5, pp. 455 - 458.

Burzin, M.B., Main Trends in Historical Evolution of Phytoplankton during the Late Precambrian and Early Cambrian, *Ekosistemnye Perestroiki i Evolyutsiya Biosfery* (Ecosystem Reorganizations and Biosphere Evolution), Moscow: Nauka, 1994, pp. 51 - 62.

Chadwick, G.H., Subdivision of Geologic Time, *Bull. Geol. Soc. Am.*, 1930, vol. 41, pp. 47 - 48.

Chen Junyuan, Precambrian Metazoans of the Huai River Drainage Area (Anhui, E. China): Their Taphonomic and Ecological Evidence, *Lethaea*, 1988, vol. 69, no. 3/4, pp. 189 - 215.

Chumakov, N.M., Laplandian Glaciation, *Etyudy po Stratigrafii* (Essays on Stratigraphy), Moscow: Nauka, 1974, pp. 71 - 96.

Chumakov, N.M., Laplandian Glaciohorizon and Its Stratigraphic Analogues, Abstracts of Papers, *Int. Symp. Terminal Precambrian and Cambrian Geology*, Yichang, Hubei, 1987, pp. 7 - 8.

Chumakov, N.M., *Dokembriiskie Tillity i Tilloidy: Problemy Dokembriiskikh Oledenenii* (Precambrian Tillites and Tilloids: Problems of Precambrian Glaciations), Moscow: Nauka, 1978.

Chumakov, N.M., The Problems of Old Glaciations (Pre-Pleistocene Glaciogeology in the USSR), *Sov. Sci. Rev., Sect. G, Geol.*, Harwood Acad., 1992, vol. 1, part 3.

Cloud, P. and Glaessner, M.F., The Ediacarian Period and System: Metazoa Inherit the Earth, *Science*, 1982, vol. 217, no. 4562, pp. 783 - 792.

Conway, M.S., The Fossil Record and the Early Evolution of the Metazoa, *Nature*, 1993, vol. 361, pp. 219 - 225.

Cowie, J.W., The Proterozoic-Phanerozoic Transition and the Precambrian-Cambrian Boundary, *Precambrian Res.*, 1981, vol. 15, pp. 199 - 206.

Cowie, J.W. and Rozanov, A.Yu., The Precambrian-Cambrian Boundary Working Group in Siberia, 1973, *Geol. Mag.*, 1974, vol. 111, pp. 237 - 253.

Cowie, J.W., Ziegler, W., and Remane, J., Stratigraphic Commission Accelerates Progress, 1984 - 1989, *Episodes*, 1989, vol. 12, no. 2, pp. 79 - 83.

Fedonkin, M.A., *Besskeletnaya Fauna Venda i Ee Mesto v Evolyutsii Metazoa* (Askeletal Fauna of the Vendian and Its Place in Evolution of Metazoa), Moscow: Nauka, 1987.

Fedonkin, M.A., *Belomorskaya Biota Venda* (*Dokembriiskaya Besskeletnaya Fauna Severa Russkoi Platformy*) [Vendian Biota from the White Sea Region (Precambrian Askeletal Fauna of the Northern Russian Platform)], Moscow: Nauka, 1981.

Fedonkin, M.A., *Organicheskii Mir Venda* (The Organic World of the Vendian), Moscow: Vses. Inst. Nauch. Tekh. Inform., 1983.

Fedonkin, M.A., Vendian Faunas and the Early Evolution of Metazoa, *Origin and Early Evolution of Metazoa*, Lipps, J.H. and Signor, Ph.W., Eds., N.Y.: Plenum, 1992, pp. 87 - 129.

Ford, T.D., Pre-Cambrian Fossils from Charnwood Forest, *Proc. Yorks. Geol. Soc.*, 1958, vol. 31, pp. 211 - 217.

Germs, G.J.B., New Shelly Fossils from the Nama Group, South West Africa, *Am. J. Sci.*, 1972, vol. 272, pp. 752 - 761.

Glaessner, M.F., Geographic Distribution and Time Range of the Ediacara Precambrian Fauna, *Bull. Geol. Soc. Am.*, 1971, vol. 82, pp. 509 - 514.

Glaessner, M.F., Precambrian Coelenterata from Australia, Africa, and England, *Nature*, 1959, vol. 183, pp. 1472 - 1473.

Glaessner, M.F., *The Down of Animal Life: A Biohistorical Study,* Cambridge: Cambridge Univ., 1984.

Gnilovskaya, M.B., Oldest Aquatic Plants of the Vendian in the Russian Platform, *Paleontol. Zh.*, 1971, no. 3, pp. 101 - 107.

Grabau, A.W., The Sinian System, *Bull. Geol. Soc. China*, 1922, vol. 1, nos. 1-4, pp. 44 - 88.

Gureev, Yu.A., *Morphological Analysis and Systematics of Vendiats, Preprint of Inst. of Geol. Sciences, USSR Acad. Sci.*, Kiev, 1987.

Hahn, G. and Pflug, H.D., Die Cloudinidae n. fam., Kalk-Röhren aus dem Vendium und Unter-Kambrium, *Lethaea,* 1985, vol. 65, nos. 4 - 6, pp. 413 - 431.

Harland, W.B., Armstrong, R.L., Cox, A.V., *et al.*, *A Geologic Time Scale,* Cambridge: Cambridge Univ., 1989.

Harland, W.B., Cox, A.W., Llewellyn, *et al.*, *Geologic Time Scale,* Cambridge: Cambridge Univ., 1982.

Harland, W.B., Hambrey, M.J., and Waddams, P., *Vendian Geology of Svalbard,* Oslo: Norsk Polarinstitut, 1993.

Harland, W.B. and Herod, W.T., Glaciation Through Time, *Ice Ages: Ancient and Modern*, Liverpool: Steel House, 1975, pp. 189 - 216.

Hoffman, H.J., Narbonne, G.M., and Aitken, J.D., Ediacarian Remains from Intertillite Beds in Northwestern Canada, *Geology*, 1990, vol. 18, pp. 1199 - 1202.

Holland, C.H., The Yangtze Platform: A Gateway to Chinese Geology, *Proc. Geol. Assoc.*, 1989, vol. 101(1), pp. 1 - 17.

Ivanovskii, A.B., *Paleontologiya Venda. Bibliografiya* (Paleontology of the Vendian. Bibliography), Moscow: Nauka, 1988.

Ivantsov, A.Yu., Ultrastructure of the Tube of *Sabellidites cambriensis* Yan. (Pogonophors? of the Vendian), *Byull. Mosk. O-va Ispyt. Prir., Otd. Geol.*, 1989, vol. 64, no. 5, p. 129.

Jenkins, R.J.F., The Concept of an "Ediacarian Period" and Its Stratigraphic Significance in Australia, *Trans. R. Soc. South Aust.*, 1981, vol. 105, part 4, pp. 179 - 194.

Keller, B.M., The Vendian, Yudomian, and Terminal Riphean, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1973, no. 1, pp. 86 - 92.

Keller, B.M., Units of the General Stratigraphic Scale of the Precambrian, *Dokl. Akad. Nauk SSSR*, 1966, vol. 171, no. 6, pp. 1405 - 1408.

Keller, B.M. and Sokolov, B.S., Vendian Complex – the First Subdivision of the Paleozoic Group, *Soveshchanie po Stratigrafii Otlozhenii Pozdnego Dokembriya Sibiri i Dal'nego Vostoka* (Conf. on Upper Precambrian Stratigraphy of Siberia and the Far East), Novosibirsk, 1962, pp. 34 - 36.

Khomentovskii, V.V., *Vend* (The Vendian), Novosibirsk: Nauka, 1976.

Khomentovskii, V.V. and Karlova, G.A., The Cambrian Lower Boundary and Principles of Its Substantiation in Siberia, *Geol. Geofiz.*, 1992, no. 11, pp. 3 - 26.

Kir'yanov, V.V., Paleontological Remains and Stratigraphy of the Baltic Group Deposits in the Volyn'-Podoliya Region, *Paleontologiya i Stratigrafiya Nizhnego Paleozoya Volyno-Podolii* (Paleontology and Stratigraphy of the Lower Paleozoic in the Volyn'-Podoliya Region), Kiev: Naukova Dumka, 1968, pp. 5 - 25.

Kir'yanov, V.V., Stratigraphic Schemes of the Cambrian, *Geol. Zh.*, 1969, vol. 29, no. 5, pp. 48 - 62.

Kir'yanov, V.V. and Chernysheva, N.E., On the Lower Cambrian Deposits of the Northern Volyn' Region and Find of the Oldest Trilobite, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1967, no. 7, pp. 119 - 125.

Knoll, A.H. and Walter, M.R., Latest Proterozoic Stratigraphy and Earth History, *Nature*, 1992, vol. 356, pp. 673 - 678.

Korenchuk, L.V. and Ishchenko, A.A., *Sedimentatsionnaya Tsiklichnost' Vendskikh Otlozhenii Pridnestrov'ya* (Sedimentary Cyclicity of the Vendian Deposits in the Dniester Region), Kiev: Akad. Nauk UkrSSR, 1981a.

Korenchuk, L.V. and Ishchenko, A.A., *Stratotipicheskie Razrezy Kanilovskoi Serii Venda Pridnestrov'ya* (Stratotype Sequences of the Kanilov Group of the Vendian in the Dniester Region), Kiev: Akad. Nauk UkrSSR, 1981b.

Landing, E., Precambrian-Cambrian Boundary Global Stratotype Ratified a New Perspective of Cambrian Time, *Geology*, 1994, vol. 22, pp. 179 - 182.

Lendzion, K., *Rozwój Kambryjskich Osadów Platformowych Polski*, Waszawa, 1983.

Les relations entre Précambrian et Cambrian. Problèms des séries intermédiaires, Paris: CNRS, 1958.

Makhnach, A.S., Bessonova, V.Ya., and Veretennikov, N.V., Stratigraphic Scheme of the Upper Precambrian of Byelorussia and Adjacent Regions, *Dokl. Akad. Nauk BSSR*, 1970, vol. 14, no. 2, pp. 150 - 153.

Makhnach, A.S., Veretennikov, N.V., Shkuratov, V.I., and Bordon, V.I., *Rifei i Vend Belorussii* (The Riphean and Vendian of Byelorussia), Minsk: Nauka i Tekhnika, 1976.

Matthews, S.C. and Missarzhevsky, V.V., Small Shelly Fossils of Late Precambrian and Early Cambrian Age: A Review of Recent Work, *J. Geol. Soc.*, London, 1975, vol. 131, pp. 289 - 304.

Menner, V.V. and Shtreis, N.A., Tectonic Aspects of the Geochronologic Scale, *Problemy Teoreticheskoi i Regional'noi Tektoniki* (Problems of Theoretical and Regional Tectonics), Moscow: Nauka, 1971, pp. 300 - 309.

Mens, K.A., Stages of Early Cambrian Sedimentation in the Baltic Region, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1981, no. 3, pp. 82 - 90.

Mens, K. and Pirrus, E., Stratigraphical Characteristics and Development of Vendian-Cambrian Boundary Beds on the East European Platform, *Geol. Mag.*, 1986, vol. 123, no. 4, pp. 357 - 360.

Meyen, S.V., *Vvedenie v Teoriyu Stratigrafii* (Introduction into the Theory of Stratigraphy), Moscow: Nauka, 1989.

Missarzhevski, V.V., *Drevneishie Skeletnye Okamenelosti Pogranichnykh Tolshch Dokembriya i Kembriya* (The Oldest Skeletal Fossils of Precambrian-Cambrian Boundary Beds), Moscow: Nauka, 1989.

Myannil', R.M., Nomenclature of Cambrian Deposits of the Baltic Region, *Izv. Akad. Nauk SSSR, Ser. Tekhn. i Fiziko-Matemat. Nauk*, 1958, vol. 7, pp. 350 - 352.

Narbonne, G.M., Trace Fossils, Small Shelly Fossils and the Precambrian-Cambrian Boundary, *Episodes*, 1987, vol. 10, no. 4, pp. 339 - 340.

Narbonne, G.M., Kaufman, A.J., and Knoll, A.H., Integrated Chemostratigraphy and Biostratigraphy of the Windermire Supergroup, Northwestern Canada: Implications for Neoproterozoic Correlations and the Early Evolution of Animals, *Bull. Geol. Soc. Am.*, 1994, vol. 106, pp. 1281 - 1292.

Obshchie Voprosy i Printsipy Raschleneniya Dokembriya (General Problems and Principles of Precambrian Subdivision), Glebovitskii, V.A. and Shemyakin, V.M., Eds., St. Petersburg: Nauka, 1994.

Patrulius, D. and Iordan, M., Asupra prezentei pogonoforului *Sabellidites cambriensis* Yan. si a "algei" *Vendotaenia antiqua* Gnil. in depozitele detritice presiluriene din podisul Moldovenesk, *Dări di seamă ale sedintelor, Vol. LX (1972 - 1973), 4, Stratigrafie*, Bucuresti, 1974, pp. 3 - 18.

Pflug, H.D., Vor- und Frühgeschichte der Metazoen, *N. Jb. Geol. Paläont. Abh.*, 1974, vol. 145, no. 3, pp. 328 - 374.

Plumb, K.A., New Precambrian Time Scale, *Episodes*, 1991, vol. 14, no. 2, pp. 139 - 140.

Putevoditel' Ekskursii po Rekam Aldanu i Lene. Mezhdunarodnaya Ekskursiya po Probleme Granitsy Kembriya i Dokembriya (Guidebook of Excursion Along Aldan and Lena Rivers. International Excursion on the Problem of Precambrian-Cambrian Boundary), Moscow-Yakutsk, 1973.

Reshenie Soveshchaniya po Stratigrafii Otlozhenii Verkhnego Dokembriya Sibiri i Dal'nego Vostoka (Resolution of the Meet. on Upper Precambrian Stratigraphy of Siberia and the Far East), Novosibirsk: Inst. Geol. Geofiz., Sib. Otd. Akad. Nauk SSSR, 1962.

Rozanov, A.Yu., The Cambrian Lower Boundary Problem, *Geol. Mag.*, 1967, vol. 104, no. 5, pp. 415 - 434.

Rozanov, A.Yu., The Precambrian-Cambrian Boundary, *Granitsy Geologicheskikh Sistem* (Boundaries of Geological Systems), Moscow: Nauka, 1976, pp. 31 - 53.

Rozanov, A.Yu. and Sokolov, B.S., Precambrian-Cambrian Boundary: Recent State of Knowledge, *Pecambrian Res.*, 1982, vol. 17, pp. 125 - 131.

Rozanov, A.Yu. and Sokolov, B.S., The Problem of the Precambrian-Cambrian Boundary, *Geol. Mag.*, 1980, vol. 117(1), pp. 23 - 27.

Rozanov, A.Yu., Missarzhevskii, V.V., Volkova, N.A., *et al.*, *Tommotskii Yarus i Problema Nizhnei Granitsy Kembriya* (The Tommotian Stage and Problem of the Cambrian Lower Boundary), Moscow: Akad. Nauk SSSR, 1969.

Savitskii, V.E., On Relationship of the Cambrian and Upper Precambrian on the Aldan Shield, *Soveshchanie po Stratigrafii Otlozhenii Pozdnego Dokembriya Sibiri i Dal'nego Vostoka* (Conf. on Upper Precambrian Stratigraphy of Siberia and the Far East), Novosibirsk, 1962, pp. 53 - 54.

Savitskii, V.E., Paleogeographic and Paleobiogeographic Aspects of Stage Subdivision of the Cambrian in the Siberian Platform, *Mezhdunarodn. Geol. Kongress, XXIV Sessiya. Doklady Sovetskikh Geologov. Paleontologiya* (International Geol. Congress, the XXIV Session. Reports of Soviet Geologists. Paleontology), Moscow: Nauka, 1972, pp. 80 - 85.

Savitskii, V.E., The Problem of the Cambrian Lower Boundary in the Siberian Platform and the Nemakit-Daldyn Horizon, *Analogi Vendskogo Kompleksa v Sibiri* (Analogues of the Vendian Complex in Siberia), Moscow: Nauka, 1975, pp. 43 - 61.

Semikhatov, M.A., Recent Concept of General Subdivision and a New Stratigraphic Scale of the Precambrian of Northern Euroasia, *Obshchie Voprosy i Printsipy Raschleneniya Dokembriya* (General Problems and Principles of Precambrian Subdivision), St. Petersburg: Nauka, 1994, pp. 9 - 26.

Sepkoski, J.J., Jr., A Kinetic Model of Phanerozoic Taxonomic Diversity: I. Analysis of Marine Orders, *Paleobiology*, 1978, vol. 4, no. 3, pp. 223 - 251.

Sepkoski, J.J., Jr., Precambrian-Cambrian Boundary: The Spike Is Driven and the Monolith Crumbles, *Paleobiology*, 1983, vol. 9, no. 3, pp. 199 - 206.

Schatsky, N.S., *Ocherki Tektoniki Volgo-Ural'skoi Neftenosnoi Oblasti i Smezhnoi Chasti Zapadnogo Sklona Urala* (Synopsis on Tectonics of the Volga-Urals Oil-Bearing Region and Adjacent Western Slope of the Urals), Moscow: Mosk. O-vo Ispyt. Prir., 1945.

Schatsky, N.S., The Proterozoic-Paleozoic Boundary and Riphean Deposits of the Russian Platform, *Izv. Akad. Nauk., Ser. Geol.*, 1952, no. 5, pp. 36 - 49.

Siedlecka, A. and Roberts, D., The Bed Rock Geology of Varanger Peninsula. Finmark, North Norway: an Excursion Guide, *Norg. Undersokelse, Spec. Publ.*, 1992, no. 5.

Sin Yu-sheng and Liu Kui-chih, *Micropaleoflora from the Sinian Sibera of W. Hubeh and Its Stratigraphic Significance*, Peking, 1976.

Sokolov, B.S., Comparative Characteristic of the Pre-Eiffelian Deposits of the Central and Eastern Russian Platform, *Geologicheskii Sbornik 2. Trudy VNIGRI. Vyp. 95* (Collection of Geological Papers 2. Proceedings of VNIGRI. Issue 95), Leningrad: Gostoptekhizdat, 1956, pp. 36 - 88.

Sokolov, B.S., Le problème de la limite inférieure du paleozoique et les dépots les plus anciens sur les plates-formes antésiniennes de l'Eurasie, *Colloq. int.*, LXXVI, Paris, CNRS, 1958, pp. 103 - 128.

Sokolov, B.S., Main Results of the International Symposium on the Precambrian-Cambrian Boundary, *Geol. Geofiz.*, 1974a, no. 4, pp. 18 - 26.

Sokolov, B.S., Metazoa of the Precambrian and the Vendian-Cambrian Boundary, *Paleontol. Zh.*, 1976, no. 1, pp. 3 - 18.

Sokolov, B.S., Oldest Lower Cambrian Deposits and Sabelliditids, *Vsesoyuznyi Simpozium po Paleontologii Dokembriya i Rannego Kembriya (Tezisy Dokladov)* [All-Union Symp. on Paleontology of the Precambrian and Early Cambrian (Abstracts)], Novosibirsk: Inst. Geol. Geofiz. Sib. Otd. Akad. Nauk SSSR, 1965, pp. 78 - 91.

Sokolov, B.S., Oldest Pogonophors, *Dokl. Akad Nauk SSSR*, 1967, vol. 177, no. 1, pp. 201 - 204.

Sokolov, B.S., Age of the Oldest Sedimentary Cover of the Russian Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1952, no. 5, pp. 21 - 31.

Sokolov, B.S., Paleontological Finds in the Pre-Usolian Deposits of the Irkutsk Amphitheatre, *Analogi Vendskogo Kompleksa v Sibiri* (Analogues of the Vendian Complex in Siberia), Moscow: Nauka, 1975, pp. 112 - 117.

Sokolov, B.S., Organic World on the Way to Phanerozoic Differentiation, *Vestn. Akad. Nauk. SSSR*, 1976, no. 1, pp. 126 - 143.

Sokolov, B.S., Some Problems of Upper Precambrian Stratigraphy and the Vendian Position, *Problemy Stratigrafii i Istoricheskoi Geologii* (Problems of Stratigraphy and Historical Geology), Moscow: Mosk. Gos. Univ., 1978, pp. 20 - 29.

Sokolov, B.S., Stratigraphic Scheme of the Lower Paleozoic (Pre-Devonian) Deposits in the Northwestern Russian Platform, *Devon Russkoi Platformy* (The Devonian of the Russian Platform), Leningrad: Gostoptekhizdat, 1953, pp. 16 - 38.

Sokolov, B.S., The Problem of the Paleozoic Lower Boundary and Oldest Deposits of the Pre-Sinian Platforms of Eurasia, *Geologicheskii Sbornik 3. Tr. VNIGRI. Vyp. 126* (Collections of Geological Papers. Proceedings of VNIGRI. Issue 126), Leningrad: Gostoptekhizdat, 1958, pp. 5 - 67.

Sokolov, B.S., The Problem of the Precambrian-Cambrian Boundary, *Geol. Geofiz.*, 1974b, no. 2, pp. 3 - 29.

Sokolov, B.S., The Vendian Period in the Earth History, *Priroda*, 1984, no. 12, pp. 3 - 18.

Sokolov, B.S., The Vendian Polychaetes, *Vendskaya Sistema. T. 1. Paleontologiya* (The Vendian System, Vol. 1, Paleontology), Moscow: Nauka, 1985, pp. 198 - 200.

Sokolov, B.S., The Vendian of Northern Eurasia, *Geol. Geofiz.*, 1971, no. 6, pp. 13 - 22.

Sokolov, B.S., The Vendian of Northern Eurasia, *Arctic Geology. Proc. Second. Int. Symp. Arctic Geology, Feb. 1 - 4, 1971*, San Francisco, CCA, Pitcher, M.G., Ed., Tulsa, OOK, USA, 1973, pp. 204 - 218.

Sokolov, B.S., The Vendian Stage in Earth History, *Mezhdunarodnyi Geol. Kongress, XXIV Sessiya. Doklady Sovetskikh Geologov. Paleontologiya* (Int. Geol. Congr., XXIV Session. Reports of Soviet Geologists. Paleontology), Moscow: Nauka, 1972, pp. 114 - 124.

Sokolov, B.S., The Vendian Stage in Earth History, *24th IGC. Section 1: Precambrian Geology*, Montreal, 1972, pp. 78 - 84.

Sokolov, B.S., The Vendian System: Position in the Stratigraphic Scale, *27 Mezhdunarodnyi Geol. Kongress. Stratigrafiya. Doklady. T. 1* (27th Int. Geol. Congress. Stratigraphy. Reports, Vol. 1), Moscow: Nauka, 1984, pp. 111 - 127.

Sokolov, B.S., The Vendian System: Pre-Cambrian Geobiological Environments, *Mezhdunarodnyi Geol. Kongress, XXVI Sessiya. Doklady Sovetskikh Geologov, Paleontologiya. Stratigrafiya* (Int. Geol. Congress, XXVI Session, Reports of Soviet Geologists. Paleontology. Stratigraphy), Moscow: Nauka, 1980, pp. 9 - 21.

Sokolov, B.S., Vendian and Early Cambrian Sabelliditida (Pogonophora) of the USSR, *Proc. IPU, XXIII Int. Geol. Congr.*, Prague, 1968, pp. 76 - 86.

Sokolov, B.S. and Fedonkin, M.A., The Vendian as the Terminal System of the Precambrian, *Episodes*, 1984, vol. 7, no. 1, pp. 12 - 19.

Sokolov, B.S. and Khomentovskii, V.V., Age of Oil and Gas-Bearing Deposits of the Southwestern Siberian Platform, *Sov. Geol.*, 1980, issue 5, pp. 45 - 56.

Stratigrafiya Verkhnedokembriiskikh i Kembriiskikh Otlozhenii Zapada Vostochno-Evropeiskoi Platformy (Stratigraphy of the Upper Precambrian and Cambrian Deposits in the Western Parts of East European Platform), Keller, B.M. and Rozanov, A.Yu., Eds., Moscow: Nauka, 1979.

Sun Weiguo, Late Precambrian Pennatulids (Sea Pens) from Eastern Yangtze Gorge, China: *Paracharnia* gen.nov., *Precambrian Res.*, 1986, vol. 31, no. 4, pp. 361 - 375.

Sun Weiguo, Wang Guixiang, and Zhou Benhe, Macroscopic Worm-Like Body Fossils from the Upper Precambrian (900 - 700 Ma), Huainan District, Anhui, China and Their Stratigraphic and Evolutionary Significance, *Precambrian Res.*, 1986, vol. 31, pp. 377 - 403.

Termier, H. and Termier, G., L'Ediacarien, premier étage paleontologique, *Rev. Gén. Sciences*, 1960, vol. 67, pp. 1 - 79.

The Sinian System of China, Peking, 1976.

The Vendian System, Vol. 1, Paleontology, Sokolov, B.S. and Ivanovskii, A.B., Eds., Berlin: Springer, 1990a.

The Vendian System, Vol. 2, Regional Geology, Sokolov, B.S. and Fedonkin, M.A., Eds., Berlin: Springer, 1990b.

Urbanek, A., Sabellitids, *Paleontologiya Verkhnedokembriiskikh i Kembriiskikh Otlozhenii Vostochno-Evropeiskoi Platformy* (Paleontology of the Upper Precambrian and Cambrian Deposits of the East European Platform), Moscow: Nauka, 1979, pp. 88 - 92.

Val'kov, A.K., *Biostratigrafiya i Khiolity Kembriya Severo-Vostoka Sibirskoi Platformy* (Biostratigraphy and Chyolithids of the Cambrian in the Northeastern Siberian Platform), Moscow: Nauka, 1975.

Val'kov, A.K., *Biostratigrafiya Nizhnego Kembriya Vostoka Sibirskoi Platformy* (Biostratigraphy of the Lower Cambrian in the Eastern Siberian Platform), Moscow: Nauka, 1982.

Val'kov, A.K., *Biostratigrafiya Nizhnego Kembriya Vostoka Sibirskoi Platformy* (Biostratigraphy of the Lower Cambrian in the Eastern Siberian Platform), Moscow: Nauka, 1987.

Vendotenidy Vostochno-Evropeiskoi Platformy (Vendotenids of the East European Platform), Gnilovskaya, M.B., Ed., Leningrad: Nauka, 1988.

Vendskaya Sistema. Istoriko-Geologicheskoe i Paleontologicheskoe Obosnovanie. T. 1. Paleontologiya (The Vendian System. Historical-Geological Substantiation, Vol. 1, Paleontology), Sokolov, B.S. and Ivanovskii, A.B., Eds., Moscow: Nauka, 1985a.

Vendskaya Sistema. Istoriko-Geologicheskoe i Paleontologicheskoe Obosnovanie. T. 2. Stratigrafiya i Geologicheskie Protsessy (The Vendian System. Historical-Geological Substantiation, Vol. 2, Stratigraphy and Geological Processes), Sokolov, B.S. and Fedonkin, M.A., Eds., Moscow: Nauka, 1985b.

Vsesoyuznyi Simpozium po Paleontologii Dokembriya i Rannego Kembriya (Tezisy Dokladov) [All-Union Symp. on Paleontology of the Precambrian and Early Cambrian (Abstracts)], Sokolov, B.S., Ed., Novosibirsk: Inst. Geol. Geofiz., Sib. Otd. Akad. Nauk SSSR, 1965.

Wang Guixiang and Zhang Shien, *Research on the Upper Precambrian of Northern Jiangsu and Anhui Provinces*, Hefei, Anhui: Anhui Press Sci. Technol., 1984.

Webby, B.D., Trace Fossils from the Lintiss Vale Formation of New South Wales: A Late Precambrian Fauna, *Search*, 1973, vol. 4, nos. 11 - 12, pp. 494 - 496.

Xing Yusheng, The Sinian System and Its Position in the Geologic Time Scale, *Sci. Pap. on Geol. Int. Exch.*, Beijing, 1984, pp. 37 - 48.

Xing Yusheng, Ding Qixiu, and Luo Huilin, Biotic Characteristics of the Sinian-Cambrian Boundary Beds in China and the Boundary Problems, *Precambrian Res.*, 1982, vol. 17, pp. 77 - 85.

Xing Yusheng, Ding Qixiu, Luo Huilin, He Tinggui, and Wang Yangeng, The Sinian-Cambrian Boundary of China and Its Related Problems, *Geol. Mag.*, 1984, vol. 121, no. 3, pp. 155 - 170.

Yanishevskii, M.E., The Cambrian Deposits of the Leningrad District, *Uch. Zap. Leningrad. Gos. Univ.*, 1939, no. 25, pp. 3 - 31.

Yarusnoe Raschlenenie Nizhnego Kembria Sibiri. Atlas Okamenelostei (The Stage Subdivision of the Lower Cambrian of Siberia. Atlas of Fossils), Sokolov, B.S. and Zhuravleva, I.T., Eds., Moscow: Nauka, 1983.

Yarusnoe Raschlenenie Nizhnego Kembriya. Stratigrafiya (The Stage Subdivision of the Lower Cambrian. Stratigraphy), Rozanov, A.Yu. and Sokolov, B.S., Eds., Moscow: Nauka, 1984.

Zhan Zhongying, Coccoid Microfossils from the Doushantuo Formation (Late Sinian) of South China, *Precambrian Res.*, 1985, vol. 28, pp. 163 - 173.

Znosko, J., W sprawie pozycji startigraficznej eokambrjiskich sparagmitów i niektórych młodoprecambrjiskich formacji, *Kwart. Geol.*, 1961, vol. 5, no. 4, pp. 737 - 774.

Stratigraphy and Geological Correlation, Vol. 3, No. 6, 1995, pp. 591 - 601. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 3, No. 6, 1995, pp. 68 - 78.
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Isotopic Age, Nature, and Structure of the Precambrian Crust of Belarus

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Abstract – The age and primary nature of the Precambrian crust of the Belarus basement were established by using the U-Pb isotope datings of accessory zircons and by means of Sm-Nd isotope studies of whole rock samples from the main structural complexes of the basement. Archean crustal material is absent in the studied structures of the larger part of Belarus. The crust of the Belarussian-Baltic granulite belt and of the Central Belarussian belt was formed during a period of 2 - 1.8 Ga in the Paleoproterozoic, thus making these formations concurrent with the Svecofennids of the Baltic shield. Archean crustal material was found only among the metapelites of the Bragin granulite block correlative with the formations of the Ukrainian shield. The new data allow us to extend the Svecofennian province of the Baltic shield to the south up to its boundary with the Osnitsk-Mikashevichi igneous belt. The crustal structure in this part of the East European platform, however, differs essentially from that of Svecofennids in the Baltic shield because of a unique alternation of the metamorphic belts. This type of crustal structure is indicative of specific geodynamic settings during the formation of the Paleoproterozoic crust in the Baltic area and in Belarus.

Key words: *Precambrian, Early Proterozoic, East European platform, crystalline basement, U-Pb isotope age, zircon, concordia, εNd(T)*

INTRODUCTION

For many years, the scientific interest of N.S. Schatsky was focused on the study of the structure of the buried basement to obtain a framework for the tectonic zoning of the East European platform (Schatsky, 1940, 1946). The publication of the first Tectonic Map of the USSR and of the International Tectonic Map of Europe (scale 1 : 2 500 000), which were elaborated with an impressive contribution by Schatsky (Schatsky and Bogdanov, 1961), now allows us to distinguish not only the relief patterns of the basement surface of the Russian plate, but also the details of the basement structure (*Mezhdunarodnaya Tektonicheskaya ...*, 1981). The vast amount of data on the composition and structure of the crystalline basement of the platform, collected in the 1970s and 1980s, made it possible to correlate the Archean and Early Proterozoic structural and lithologic complexes of plate and shield and to trace the continuations of the early Precambrian structures of the shield into the platform by using geophysical and borehole data (*Metamorficheskie Kompleksy ...*, 1978; *Osnovnye Problemy ...*, 1979; *Geologiya, Petrologiya ...*, 1976; Bogdanova, 1986; *Geologiya i Perspektivy ...*, 1987; and others). In the course of these studies, however, the adequacy of the correlated complexes and structures in the shield and basement of the Russian plate was unfortunately disregarded, and their geologic features were compared almost exclusively by using data on rock composition with little or no geochronological verification.

This problem becomes particularly acute when correlating the early Precambrian complexes of the western and eastern parts of the Russian plate. These complexes were always visualized as Archean owing to their similarity to the highly metamorphosed rock complexes of the Baltic and Ukrainian shields. While isotope datings confirm this only for the Volga-Ural segment (Bogdanova, 1986; Bibikova *et al.*, 1994), the Archean age of the granulites and of the entire sequence of the crust-forming events in the western part of the plate was determined by a single age measurement in the Belarussian granulites (about 2580 Ma) using Pb-Pb whole rock data (Sobotovich *et al.*, 1976; Aksamentova and Naidenkov, 1991; Pap, 1992). Moreover, the reliably dated Early Paleoproterozoic granitoids in this area, including charnockitoids (Bibikova *et al.*, 1982; Shcherbak *et al.*, 1990) are usually considered to be associated only with the transformations in the Archean crust.

Meanwhile, from standpoints of tectonics and geophysics, the crustal structures of the western regions of the platform have an obvious similarity with the Paleoproterozoic Svecofennian province of the Baltic

shield (Ryka, 1984; Bogdanova, 1986; Gorbatschev and Bogdanova, 1993).

At present, the study of the crust in the western regions of the East European platform has acquired particular importance in connection with the activities of several international projects. Among these works are: project no. 275, "The Deep Geology of the Baltic Shield," and no. 371, "The Structure and Correlation of the Precambrian in Northeastern Europe and the North Atlantic Region," the International Geological Correlation Program (IGCP), and the project EUROPROBE (the International Lithosphere Program). Accordingly, we now have to reassess earlier notions when compiling the new International Tectonic Map of Europe and Adjacent Territories (scale 1 : 5 000 000).

The territory of Belarus is of crucial importance for geological-geophysical and geodynamical interpretations of the formation history of the Precambrian crust in the entire western part of the Russian plate. The significance of the region resides in the fact that its crystalline basement is studied in greater detail than in other regions of the plate, and that it is situated at the junction between the structures of the Ukrainian and Baltic shields. These two shields, as we believe, belong to different segments of the East European craton, i.e., to the Fennoscandia and Sarmatia, which experienced different histories of crustal evolution (Bogdanova, 1993).

In this article we discuss the results of the U-Pb isotope dating of zircons from the rocks of the main structural complexes of the Belarus basement; some of the samples were likewise submitted to a Sm-Nd isotopic study to evaluate the age and origin of the crust in the region.

MAIN TECTONIC STRUCTURES OF THE BELARUS CRYSTALLINE BASEMENT

In Belarus, the crystalline basement located at depths varying from dozens of meters to 5 km is penetrated by about 4000 boreholes. A detailed geological map of the region's basement was drawn using the combined results of drilling, detailed interpretation of geophysical anomalies, and seismic data (Aksamentova and Naidenkov, 1991). This map, along with the recently published map of the Precambrian basement of the Gulf of Finland and the adjacent territory (*Precambrian Basement ...*, 1994) and maps of the basements in Lithuania and Poland (Kubiski and Ryka, 1982) represent the crustal structure of Belarus as a series of arching belts of north-northeastern or meridional strike; they are composed of either granulites or the rocks of amphibolite and epidote-amphibolite facies, and also of various granitoids. The belts are 500 - 700 km long, and include numerous intrusions of anorogenic granitoids of the anorthosite-rapakivi-granite formation associated with sedimentary-volcanogenic complexes.

The geological map of Belarus basement (Aksamentova and Naidenkov, 1991) shows, in passing from southeast to northwest, the following tectonic elements: the Bragin granulite block, the Osnitsk-Mikashevichi igneous belt, the Central Belarussian belt, and the Belarussian-Baltic granulite belt.

The first two structures are directly related to those of the Ukrainian shield. The Bragin granulite block consists of metasedimentary granulites and migmatites, which are referred to the lower Archean Kulazh Group (Aksamentova and Naidenov, 1991). The Osnitsk-Mikashevichi (Volyn'-Poles'e) igneous belt stretching to the northwestern margin of the Ukrainian shield is composed of metabasalts, metadiabases, metaandesites, metakeratophyres and comagmatic plutonic rocks mostly represented by granodiorites and granites. By analogy with the corresponding structures of the Ukrainian shield (the Osnitsk complex), the belt is referred to the Early Proterozoic. The rocks are metamorphosed under conditions of the low amphibolite facies (Khvorova and Utingof, 1982; Aksamentova and Naidenkov, 1991). The U-Pb age of zircons from the granitoids of the Osnitsk-Mikashevichi belt in Ukraine and Belarus is 1970 ± 10 Ma (Shcherbak *et al.*, 1990), whereas the host metavolcanic rocks enclosing these granitoids (the Kless Beds) on the territory of Ukraine are 2020 and 1970 Ma old (Shcherbak, 1991).

The Osnitsk-Mikashevichi belt contains younger and slightly metamorphosed sediments and volcanics (the Zhitkovichi Complex) associated with granites of the rapakivi type, which are about 1800 Ma old (Shcherbak *et al.*, 1990). Further south in the Ukrainian shield, the age of the rapakivi-anorthosite Korosten Complex, determined by different isotopic methods, is 1800 - 1750 Ma (Shcherbak, 1991).

The Central Belarussian structure is located northwest of the Osnitsk-Mikashevichi belt, and includes the 200-km-long Okolova metavolcanic belt, composed of metamorphic basalts, basaltic andesites, andesites, and dacites (Makhnach *et al.*, 1974; Kornilov *et al.*, 1988). The metavolcanites contain thick sequences of ferruginous quartzites, metacarbonates, and graphitic slates. The rock composition in this volcanic belt implies its formation in an island arc setting. The Central Belarussian belt also has amphibolites, the amphibole- and biotite-bearing gneisses, and migmatites, which are referred to the Upper Archean Ozera Group (Aksamentova and Naidenkov, 1991). The isotopic age of igneous zircons from metavolcanites of the Okolova belt was determined by the U-Pb method to be 1980 ± 20 Ma (Bibikova *et al.*, 1992). The granites intruding into the Okolova volcanites yielded zircon ages of 1890 ± 35 Ma (Shcherbak *et al.* 1990). Both the gneisses and supracrustal rocks of the belt were metamorphosed under T = 560 - 600°C and P = 5 - 8 kbar (Aksamentova and Naidenkov, 1991). To the west, the degree of metamorphism increases up to the conditions of the granulite facies, which also partially affect the western distribution area of the Okolova Group.

The great Belarussian-Baltic granulite belt is situated in the northwestern part of Belarus, extending throughout Estonia and southeastern Lithuania. On the geological map of Belarus, the granulites are referred to the Lower Archean Shchuchin Group (Aksamentova and Naidenkov, 1991). The granulite belt is exposed as a system of granulite lenses 5 - 30 km wide and 80 - 250 km long; they are divided by narrow, steeply dipping zones of blastomylonites (Aksamentova *et al.*, 1994). In these zones, the granulites are regressively altered under conditions of the amphibolite facies.

The granulites are represented mainly by mafic two-pyroxene orthorocks associated with the enderbite-charnockite plutonic series. Also abundant are high-Al metapelitic gneisses. Though the age of the enderbites is determined to be 1800 Ma, the granulites are commonly considered as Archean rocks on the basis of a sole age determination (2580 Ma) obtained by whole rock dating using the Pb-Pb method mentioned earlier (Sobotovich *et al.*, 1976). The reliability of such granulite datings, however, has long since been doubted (Wasserburg and Jacobsen, 1978).

It is very important to correctly estimate the age of granulites used as the Early Archean reference complex in stratigraphic correlations with the shield complexes (Aksamentova and Naidenkov, 1991). We, therefore, conducted the U-Pb isotope dating of zircons from the metasedimentary granulites and migmatitic granites of the Bragin granulite block and from the mafic granulites of the Shchuchin Group of the Belarussian-Baltic granulite belt. We also measured isotopic ages of metavolcanites from the Okolova Group and of gneisses of the amphibolite facies from the Ozera Group of the Central Belarussian belt.

DESCRIPTION OF THE DATED ROCKS AND ZIRCONS

Granulites of the Bragin block. On the territory of the Bragin block, more than sixty drilled boreholes demonstrated the homogeneity of its crystalline rocks. As attested by Aksamentova *et al.* (1977), the rocks consist mostly of fine-grained moderately aluminiferous gneisses corresponding in composition to metagreywackes and migmatites. The metamorphism of the granulite facies is indicated by the mineral paragenesis of hypersthene, pyrope garnet, high-Ti biotite, and sillimanite associated with minor cordierite, plagioclase, and quartz. The cores recovered from the Bars-60 site (Fig. 1) were used for the isotope dating of granulites. The hole penetrated down to about 600 m into the basement, and at depths of 3650 - 3661 m, reached biotite-garnet plagiogranites and granites with restites of metasedimentary granulites. The larger part of granitoids and gneisses is transformed into blastomylonites and retrogressively altered under conditions of the amphibolite facies.

The metasedimentary gneiss, recovered from a depth of 3661 m, is a massive, almost black fine-augen blastomylonite, representing the strongly deformed and recrystallized migmatite of garnet-biotite-sillimanite gneiss with graphite. The composition of augens not larger than 5 mm suggests that the original mineral association of the granulite facies consisted of andesine-oligoclase, garnet, microperthitic K-feldspar, reddish-brown biotite, sillimanite, and quartz. These augen areas also have zircons, monazite, apatite, sphene, rutile, and graphite. The fine-grained rock matrix contains brownish biotite, often associated with fibrolite and feldspar recrystallized into fine aggregates.

In this sample, forms of accessory zircons vary from short-prismatic to isometric crystals with smooth contours and numerous opaque inclusions (Fig. 2.1). There are two types of zircons differing in color and transparency. Some of its grains are gray and semitransparent or opaque, while others are almost colorless and transparent. The latter feature is probably an indication that transparent grains originated during the metamorphic recrystallization of terrigenous zircon grains in metasediments under conditions of the granulite facies.

At a depth of 3653 m, the somewhat gneissoid coarse-crystalline granite contains elongated restitic segregations of biotite, large crystals of violet garnet, and lenslike quartz aggregates. Gray oligoclase, orange-pink microcline, and quartz constitute about 80% of the rock mass. The accessory zircon is represented by large, perfectly shaped idiomorphic prismatic grains with well developed pyramid faces (Fig. 2.2). These zircons are brown, semitransparent or opaque and, as we shall demonstrate below, highly enriched in uranium.

The mafic granulites of the Belarussian-Baltic granulite belt. The mafic granulites from the Iv'e block are the most typical of the central part of the belt. In fact, these rocks were used to substantiate the idea that the Early Archean proto-oceanic stage was the formation time of the c rust in the region (Aksamentova and Naidenkov, 1987). The mafic granulite, recovered from a depth of 184 - 197 m, borehole IV-192 (Fig. 1), is almost black, and contains coarse to medium-grained metagabbro obviously gneissoid at the scale of mm- to cm-thick bands. The bands show various proportions of ortho- and clinopyroxenes, greenish-brown hornblende, plagioclase (ranging from bytownite to andesine), titanomagnetite, ilmenite, and apatite. Quartz is also locally present. The accessory minerals are zircon, sphene, and apatite. The likelihood of magmatic layering is indicated by several feature of the rock, such as the relics of gabbro texture with subidiomorphic elongated crystals of plagioclase, the presence of ortho- and clinopyroxenes with traces of desintegration, the high though varied contents of Mo, Ti, P, V, Co, Sc (Naidenkov and Aksamentova, 1983), the high Ti, Fe but low Al contents in hornblende, and the numerous ore mineral inclusions. The rock often shows

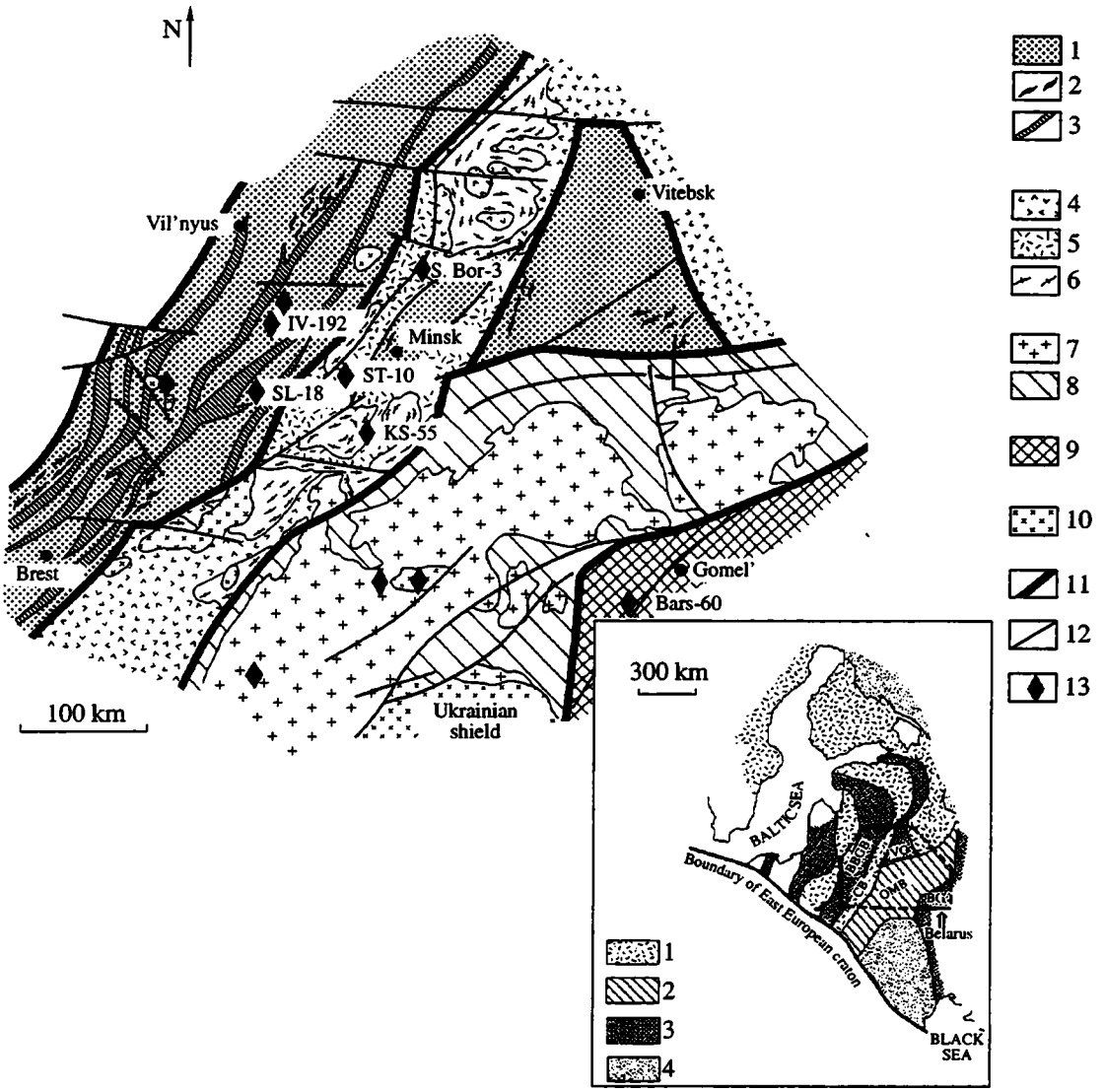

Fig. 1. Structural scheme of the crystalline basement in Belarus (after Aksamentova and Naidenkov, 1991; simplified).

Belarussian-Baltic granulite belt and Vitebsk granulite block: 1 – granulites, charnockites, manzonites; mangerites, etc.; 2 – retrogressively altered granulites; 3 – blastomylonization zones. Central Belarussian belt: 4 – gneisses of amphibolite facies; 5 – Okolova volcanic belt; 6 – migmatites. The Osnitsk-Mikashevichi belt: 7 – volcano-plutonic complex of metabasalts, leptites, and granitoids; 8 – gneisses. The Bragin granulite block: 9 – metapelitic granulites; 10 – anorogenic granitoids, rapakivi type; 11 – boundaries of tectonic units; 12 – faults; 13 – boreholes sampled for geochronological studies. The names are given for core samples discussed in the paper and dated using the zircon U-Pb method and whole rock Sm-Nd method.

Inset: 1 – early Proterozoic granite-gneiss areas; 2 – Osnitsk-Mikashevichi magmatic belt; 3 – granulite belts in the basement of East European platform; 4 – Archean provinces.

BBGB – Belarussian-Baltic granulite belt; CB – Central Belarussian belt; OMB – Osnitsk-Mikashevichi (Volyn'-Poles'e) belt; VG – Vitebsk granulite block; BG – Bragin granulite block.

metamorphic polygonal granular texture. The data on P-T parameters show partial recrystallization of the rock under conditions of 750 - 800°C and 5 - 8 kbar.

Two zircon generations are identified in the rock. The earlier generation is represented by short-prismatic, brown, semitransparent grains with smoothed contours frequently coated with transparent, second generation zircon (Fig. 2.3). The latter generation forms separate isometric grains which are transparent and colorless, with the diamond luster of numerous facets ("the granulitic zircon," Fig. 2.4).

The Central Belarussian belt: metadacites of the Okolova Group and gneisses of the amphibolite facies (the Ozera Group). The zircon from the Okolova metadacite, borehole ST-10, was analyzed complementary to the zircon from borehole KS-55 dated earlier (Bibikova *et al.*, 1991). The studied rock is from a lower part of the Okolova Group, directly underlying

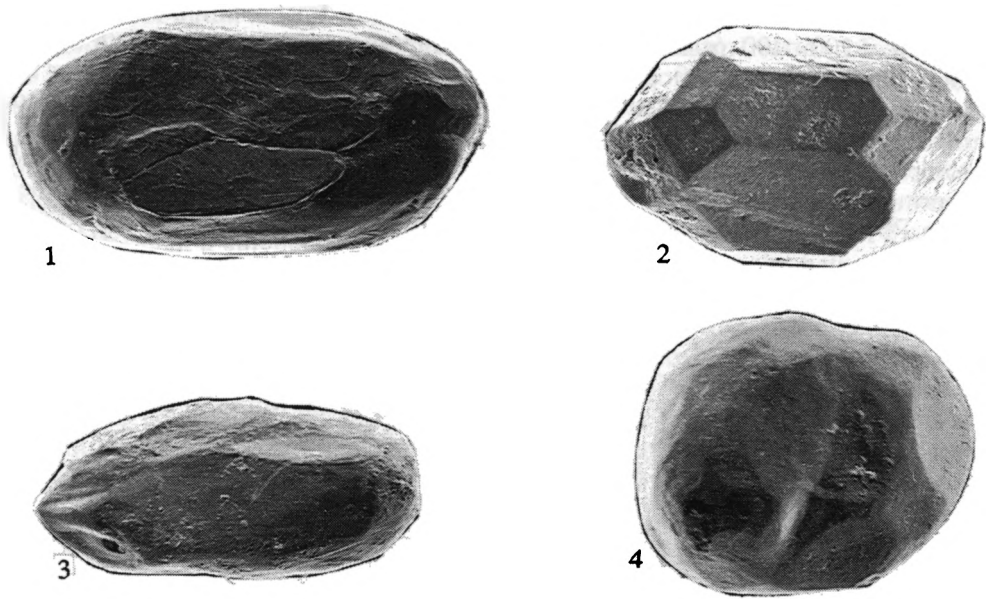

Fig. 2. Morphological types of accessory zircons in studied rocks.
1 – in metapelite from Bars-60; 2 – in migmatite granite from Bars-60; 3, 4 – in mafic granulite from IV-192: 3 – magmatic zircon, 4 – metamorphic zircon.

the main member of ferruginous quartzites. The sample is an amphibole-biotite gneiss with relics of porphyritic texture formed by small (1 to 2 mm) oligoclase crystals set in a fine-grained matrix composed of amphibole, biotite, oligoclase, and quartz associated with minor epidote and garnet. The accessory minerals are apatite, zircon, magnetite, sphene, and pyrite. The zircons were evidently crystallized from the melts, and are represented by transparent, well-shaped prismatic grains, often with intact inner fine zonality.

Amphibolites and amphibole plagiogneisses are most frequent in the rocks framing the Okolova metavolcanic belt (Fig. 1). These rocks do not contain relics of the granulite facies minerals, and their metamorphic paragenesis corresponds to the amphibolite facies (640 - 680°C and 4 to 6 kbar), thus being similar to the retrogressive paragenesis in the granulites of the Belarussian-Baltic belt. Respectively, Belarussian geologists consider them to be rocks of a separate Late Archean complex, which is younger than the granulites of the Belarussian-Baltic belt. The intermediate to acidic volcanites, some sediments, and intrusive diorites and granitoids similar to those from the borehole (Sosnovyi Bor-3 in Fig. 1) which were dated earlier, could be the protoliths of the Ozera Complex.

The metadiorite gneiss from S. Bor-3 borehole is a dark, greenish, medium-grained gneissoid rock. Its early mineral association includes dark green hornblende and andeşine, with numerous inclusions of long-prismatic apatite, dark zircon, quartz, and titanomagnetite. The well-shaped prismatic grains of plagioclase point to the magmatic origin of the rock. The younger fine-grained aggregate of schistose zones contains biotite, oligoclase, fine sphene-oligoclase-quartz simplectite substituting plagioclase and sphene substituting titanomagnetite. As shown by experiments, the crystallization of such sphene-oligoclase-quartz parageneses could occur at about 600°C and under 6 to 7 kbar provided the water saturated conditions (Van der Laan and Wyllie, 1992). The occurrence of these segregations within the rock schistosity zones implies that metamorphic transformations of quartz diorite were almost concurrent with the termination of magmatic crystallization of the intrusion.

Zircons from the studied rock have the shape of prismatic grains with the elongation coefficient of 3 to 4 and smooth contours; they are brown, transparent or semitransparent. Large zircon grains have biotite and ore mineral inclusions; some of them show noticeable inner cores, and we used the mechanical abrasion to clean one of the fractions of the mineral. The morphological and geochemical characteristics of these zircons suggest their magmatic genesis.

METHODS OF ANALYSIS

The uranium-lead isotope method. The isotope analysis of zircons was carried out at the Laboratory of Isotope Geology of the Swedish Museum of Natural History in Stockholm. In general, the procedure follows the Krogh method (Krogh,1973). After the hydrothermal desintegration in the mixture of HF and HNO_3 acids, the sample solution in 3 N HCl was divided into aliquota to measure the isotopic composition of lead and to determine the concentration of uranium and lead by using the mixed $^{208}Pb + ^{235}U$ spike. The separation

of lead and uranium for isotopic studies was conducted using anionite AG 1 × 8 of 200 - 400 mesh. The contamination of the total blank run was 30 pg of lead. The isotope analysis was carried out in a static regime with the multicollector mass spectrometer Finnigan MAT-261. The isotope composition of lead was determined by using thermoion emission, with silicogel as the ion emitter. The Pb-isotope ratios were corrected for the mass fractionation. The adopted values of decay constants were used to calculate the ages (Steiger and Jager, 1975). The age correction for the common lead admixture was determined according to the Stacey and Kramers model (Stacey and Kramers, 1975). Regression analysis of isotopic data was carried out using the Ludwig program (Ludwig, 1991). The IV-192 sample was analysed at the Vernadsky Institute of Geochemistry, RAS, by applying a method described in an earlier publication (Bibikova *et al.*, 1992).

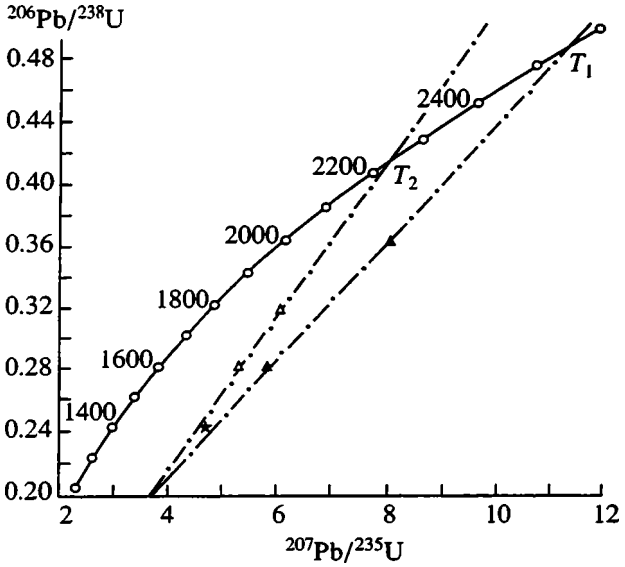

Fig. 3. Concordia diagram for zircons from metapelites of Bragin granulite belt; borehole Bars-60; depth 3661 m. Filled triangles – predominantly clastic zircon. Open triangles – predominantly metamorphic zircon. Asterisk – mixed zircons. T_1 – 2560 ± 10 Ma; T_2 – 2230 ± 7 Ma.

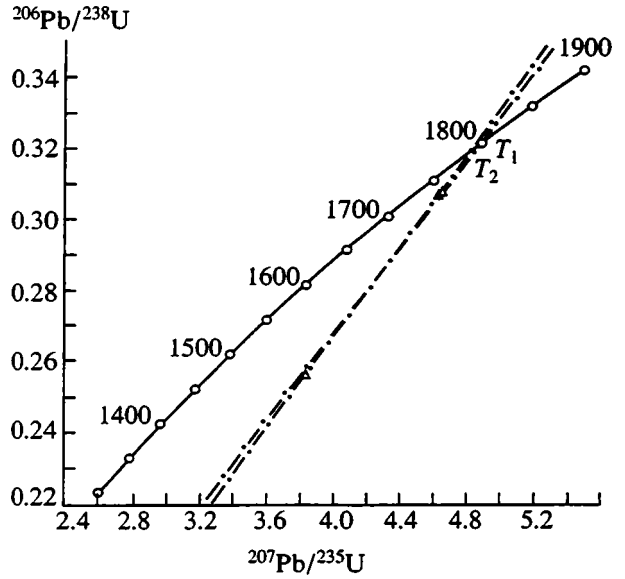

Fig. 4. Concordia diagram for zircons form the mafic granulite; borehole IV-192; filled triangles – magmatic zircons; open triangles – metamorphic zircons. T_1 – 1800 ± 4 Ma; T_2 – 1700 ± 8 Ma; MSWD – 1.5.

The samarium-neodymium isotope analysis. The Sm-Nd isotope study was conducted using the conventional method adopted at the Isotope Laboratory of the Swedish Museum of Natural History in Stockholm. After the addition of the mixed ^{147}Sm + ^{150}Nd spike, each sample was desintegrated with concentrated HF in a Teflon container during 2 to 3 days at 200°C. The REE in sum were extracted from the HCl solution using cationite AG 50W × 8 with 200 - 400 mesh in HCl. In order to separate the rare earth elements in a form of NH_4^+ compounds, the cationite AG 50W × 12 of <400 mesh was used. The 0.22 M solution of alpha-hydroxyisobutyric acid of about 4.7 pH was applied as the eluante. The total contamination of the blank run was 300 pg for Nd and 100 pg for Sm. The extracted material was fixed on the Re-ribbon to be evaporated as metal ions in the ion source with the two-ribbon configuration. The measurements were carried out with the Finnigan MAT-261 mass spectrometer. All calculations were made using the recommended constants (Wasserburg *et al.*, 1981). The Nd-isotope ratios were corrected for the fractionation relative to the value of $^{146}Nd/^{144}Nd = 0.7219$. The La Jolla standard was used as the reference sample. The table and plots (Figs. 3 - 7) present a summary of our results.

RESULTS AND DISCUSSION

Granulites of the Bragin block. The age of zircon from the migmatite granite shows that the migmatization stage ceased 2030 ± 18 Ma ago. The extremely high uranium content in zircons reaching 2700 ppm is typical of the amphibolite but not of the granulite facies of metamorphism.

The ages of all the zircon fractions from the metasedimentary gneiss are discordant (Fig. 3). The transparent zircon contains considerably less uranium, thus implying its possible formation in the course of the recrystallization of the protolithe zircon under granulite facies conditions. The zircons have experienced at least two disturbance stages which affected their U-Pb isotopic systems; i.e., during the metamorphism of the granulite facies and under exogenic conditions. Consequently, respective data points should plot within a triangle limiting the ages of these events. The available data are insufficient for adequate age determination of these events, and we can only speculate about the possible age limits. For example, the gneiss proto-

lith should be older than 2555 Ma, the age of the upper intersection of discordia with concordia for the protolithe zircon. The zircon age of the migmatite granite can be assumed as the minimal age of the granulite facies metamorphism (2030 Ma) because the migmatization under conditions of retrogressive amphibolite facies and considerable supply of uranium already ceased at that time. The maximal age of the granulite facies metamorphism is presumably 2300 Ma, as derived from the upper intersection of discordia plotted for transparent recrystallized zircon grains of the protolith. We believe that the age of granulite metamorphism is closer to the lower limit; i.e., to approximately 2100 Ma, because the zircon grains could have only been partly recrystallized and could have retained a considerable amount of ancient lead.

Granulites of the Belarussian-Baltic belt. The magmatic (prismatic) fraction of zircon from the mafic granulite (hornblende metagabbro) has a concordant age value of 1802 ± 2 Ma, whereas the discordia age for two zircon fractions is 1800 ± 4 Ma (Fig. 4). The metamorphic ("granulite") zircon from the sample is extremely fractured, which apparently resulted in a higher discordance of the U-Pb ages. The age of the upper intersection point between discordia and concordia is 1790 ± 8 Ma for this zircon fraction. The obtained ages coincide with those of magmatic zircon from enderbite recovered in borehole Slonim-18 (Shcherbak *et al.*, 1990). The εNd value approaching zero (Fig. 5) in the mafic granulite rocks suggests an age agreement between the protolith and derived metamorphic rock, and a small admixture of older, presumably Early Pro-

Isotope age of zircons from the rocks of Belarus basement

No.	Size of fraction, μm	Weight, mg	Content, ppm		Pb-Isotope composition			Isotopic ratios		Age, Ma
			Pb	U	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$
Bragin granulite massif										
Migmatite granite, borehole Bars-60, depth 3653 m										
1	+125	1.5	125	2695	300	7.076	4.347	0.4933	0.03739	1542
2	−100 + 75	1.8	128	2248	942	8.275	16.324	0.8170	0.05562	1741
3	−75	1.5	166	2192	887	7.914	11.033	1.0934	0.07128	1820
Granulite borehole Bars-60, depth 3661 m										
4	+100op.	0.1979	229.7	567.5	2750	6.029	7.8920	8.0607	0.3622	2470
5	+75op.	0.1645	186.6	605.6	3040	6.4140	8.4385	5.8614	0.2799	2367
6	−75mix.	0.4916	167.2	627.8	2840	6.8940	7.9198	4.6974	0.2422	2235
7	+100tr.	0.1898	129.9	386.7	4630	6.8046	7.8708	6.0917	0.3057	2282
8	+75tr.	0.1218	147.8	484.2	3290	7.0655	8.3727	5.3356	0.2805	2201
Central Belarussian belt										
Metadacite, borehole ST-10										
9	+100	0.1942	40.83	118.6	1660	8.0934	9.7350	5.2242	0.3245	1907
10	+75	0.1076	52.13	142.5	6300	8.1680	11.2120	5.8827	0.3519	1975
11	−75	0.3414	52.19	143.3	1240	7.7400	8.4810	5.4892	0.3359	1934
Gneiss, borehole S. Bor-3										
12	+125	0.6833	193.0	534.14	17000	8.5372	9.148	5.4943	0.3422	1902
13	+100	0.5661	194.95	602.93	10000	8.5480	8.231	4.8357	0.3030	1981
14	−100	0.1586	187.82	613.74	13000	8.6060	8.002	4.5541	0.2866	1884
15	+100ab.	0.2227	212.14	586.93	24000	8.4950	7.715	5.4450	0.3368	1914
Belarussian-Baltic granulite belt										
Mafic granulite, borehole IV-192										
16	+75pr.	2.1	187.6	514.2	3800	8.7873	5.195	4.9000	0.3230	1802
17	+100pr.	2.4	110.3	312.0	4350	8.8778	5.176	4.6185	0.3056	1793
18	+100is.	1.8	38.4	145.6	3300	8.8715	10.858	3.8509	0.2568	1778
19	+75is.	3.2	41.1	134.3	2200	8.7719	9.560	4.3110	0.2900	1764
20	−75is.	2.4	86.3	254.7	5000	8.8897	4.840	4.4660	0.2972	1782

Note: Zircons: op. – opaque; tr. – transparent; mix. – mixed; pr. – prismatic; is. – isometric; ab. – abraded.

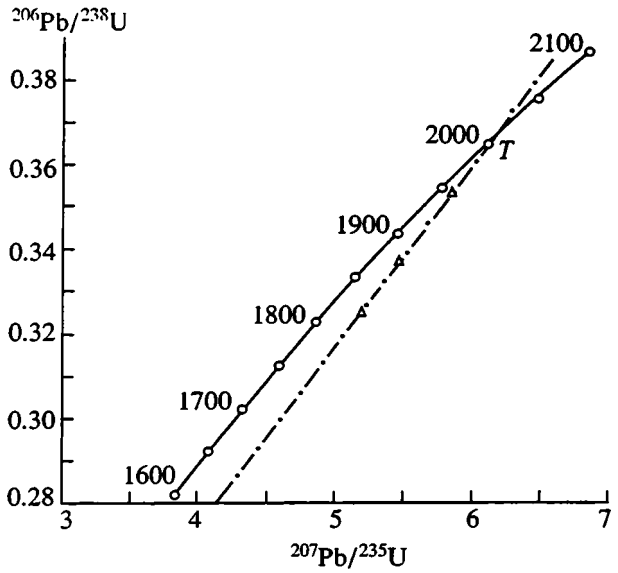

Fig. 5. Concordia diagram for zircons from metadacite; borehole ST-10; T – 1998.6 ± 6.3 Ma; MSWD – 1.6.

terozoic material in the granulite substratum. This is characteristic of the mafic granulites discussed in this paper, as well as of the enderbites and metasedimentary granulites (Fig. 1).

The Central Belarussian belt: volcanites of the Okolova Group; boreholes ST-10 and ST-38zh. The zircon age of metadacite form borehole ST-10 is 1998 ± 10 Ma according to the upper intersection of discordia with concordia (Fig. 5). This dating agrees with the age of 1982 ± 26 Ma measured earlier in the metadacite lying somewhat higher in the section of borehole KS-55 (Bibikova *et al.*, 1992). The uranium content and Th/U ratio in zircons correspond to their magmatic genesis. The Pb-isotope composition in galenite from borehole ST-38 is as follows:

$^{206}Pb/^{204}Pb$ = 15.425 ± 0.012; $^{207}Pb/^{204}Pb$ = 15.217 ± 0.014; $^{208}Pb/^{204}Pb$ = 35.004 ± 0.040; $^{207}Pb/^{206}Pb$ = 0.9866 ± 0.00014; $^{208}Pb/^{206}Pb$ = 2.2990 ± 0.0016.

These values correspond to those characterizing the 1950 - 2000 Ma interval of the Stacey and Kramers model (Stacey and Kramers, 1975) and imply that the ore leads are syngenetic with the volcanic stage.

Gneisses of the amphibolite facies from borehole S. Bor-3. Zircons from these gneisses show low uranium concentrations and insignificantly discordant ages. Their fraction with a grain size of +125 μm revealed the concordia age value of 1902 ± 2 Ma, and three other fractions differentiated in size, except the one subjected to mechanical abrasion, which showed the discordia age of 1902.7 ± 2 Ma. According to the $^{207}Pb/^{206}Pb$ ratio, the age of the abraded zircon fraction is somewhat greater; i.e., 1915 Ma (Fig. 6). The model of the two-stage crystallization of the quartz metadiorite was discussed above. The age of 1915 Ma may correspond to the first stage, whereas the final crystallization of the melt and the amphibolite facies metamorphism occurred about 1902 Ma ago. The Zhukhovichi granite intruding into the Okolova Group is of the same age (Shcherbak *et al.*, 1990).

Our data implies that the volcanism of the Okolova Group and subsequent granitoid magmatism were juvenile in origin. The respective εNd value (Fig. 7) is +2.66, which is insignificantly lower than the value for depleted

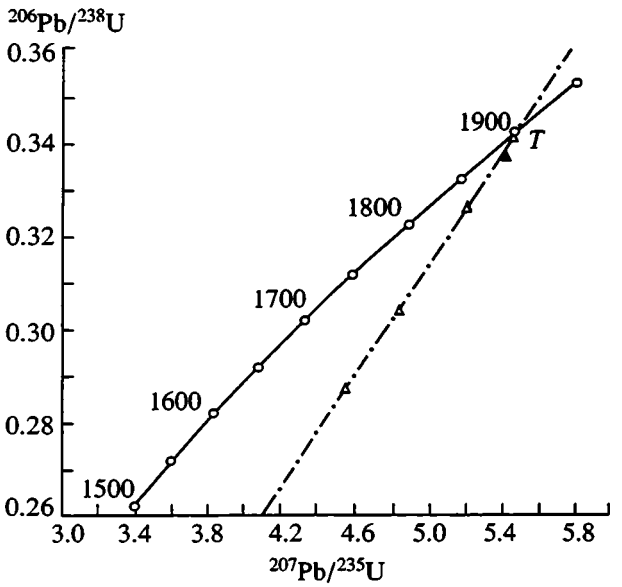

Fig. 6. Concordia diagram for zircons from gneisses; S. Bor-3. Filled triangle for abraded zircon fraction. T – 1902.7 ± 2 Ma; MSWD – 0.69.

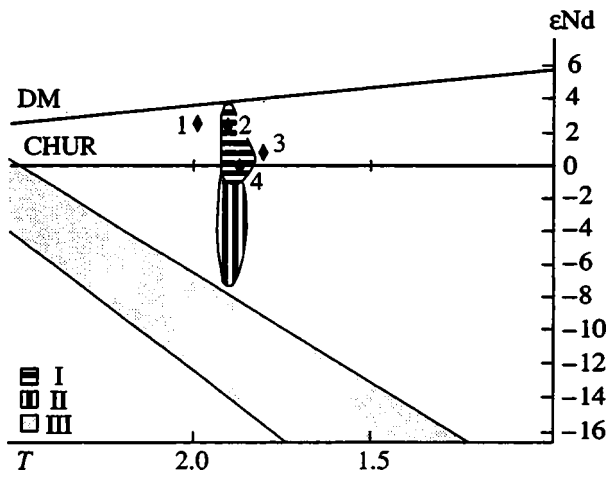

Fig. 7. Coordinates in diagram εNd–T for different rocks of Belarus, including data for the Baltic shield.

I – Svecofennian granitoids; II – Svecofennian metasediments; III – Archean crust; DM – depleted mantle after DePaolo (1981); CHUR – chondritic earth. 1 – metadacite; borehole ST-10; 2 – gneiss; borehole S. Bor-3; 3 – mafic granulite; borehole IV-192; 4 – enderbite; borehole M-8.

mantle of that age in DePaolo's model (DePaolo, 1981). Other researchers (Huhma,1984; Claesson, 1987) also commented on the somewhat lesser depletion of the Early Palaeoproterozoic mantle of the Baltic shield, as compared, for example, to the Canadian shield.

CONCLUSION

The dating of rocks from the crystalline basement by means of the Sm-Nd model method for whole rock samples and the U-Pb method for zircons do not show that Archean crustal material is present in the studied structures of the early Precambrian crust of Belarussia. The earth's crust in the Belarussian-Baltic granulite belt and in the Central Belarussian belt seems to be juvenile in origin, formed during the Paleoproterozoic interval lasting from 2.0 to 1.8 Ga. The same results were obtained for the rocks of the crystalline basement in different parts of the Baltic region, where they continue the Belarussian structures; i.e., for granulites of southern Estonia (Puura and Huhma, 1993), and for granulites, gneisses, and granitoids in Lithuania and Latvia (Mansfeld *et al.*, 1993). The isotopic, geochronological, and geochemical data indicate a similarily between the crust of the Baltic-Belarus region and the early Precambrian crust of the Svecofennian province of the Baltic shield (Huhma *et al.*, 1991).

In accordance with the new data, the granulites of the Belarussian-Baltic belt are less ancient than the metavolcanites of the Okolova Group and the amphibolite facies gneisses of the Central Belarussian belt, whose age is 2.0 - 1.9 Ga. As compared to similar volcanic belts of the Svecofennian area in Finland and Sweden, which were formed 1.93 to 1.83 Ga ago (Gorbatschev and Bogdanova, 1993b), the Okolova belt is more ancient. The data shows that this belt could have been an analog to embryonic (oceanic) island arcs of the Phanerozoic.

The mafic granulites of the Belarussian-Baltic belt located further east were formed later, about 1.8 Ga ago, soon after the crystallization stage of the gabbrotholeiitic magma. The gabbro and coeval subalkaline enderbite and charnockite of the Slonim and Osmolovo type (Arkhipova, 1984) represent the bimodal magmatic series formed during the postorogenic (postcollision) extension period of the belt. Originally, the Belarussian-Baltic and Central Belarussian structures probably were situated in a single crustal province which was later transformed by a collision processes into several metamorphic belts.

Consequently, the Svecofennides of the Baltic shield may be extending into the Russian plate up to the Osnitsk-Mikashevichi-Volyn'-Poles'e belt. The types of geological formations in this belt (Aksamentova and Naidenkov, 1991; Sveshnikov *et al.*, 1993) allow us to consider it as an analog of magmatic belts of active continental margins of the Andean type. This similarity can account for the belt's conformity with the westnorthwestern boundary of the Sarmatian segment (including the Ukrainian shield and Voronezh massif), as well as for the sharp discordance of the Osnitsk-Mikashevichi belt with other Belarussian structures. The Sarmatian segment differs from the other crustal segments of the East European craton, Fennoscandia, and the Volga-Ural region (Bogdanova, 1993), showing a unique manner of crustal formation during the Archean and Paleoproterozoic. The εNd values (from +1.5 to +2.4) obtained for metavolcanites and granitoids of the belt (Fig. 7) imply a juvenile (mantle) character of magmatism developed in an active continental margin.

This could also be responsible for the more ancient age of rocks from the Bragin granulite block of Sarmatia, the northwestern part of which includes abundant metapelites and metagreywackes bearing the Archean detrital zircons often metamorphosed under the granulite facies conditions, for instance, the Teterev and Bug groups of the Ukrainian shield (Shcherbak, 1991). The dated rocks from the Bars-60 borehole belong to the same groups.

To conclude, we consider it necessary to emphasize that the isotopic-geochronological data on rocks from different structures in the western part of the East European platform and, in particular, the described results on the crystalline basement of Belarussia, confirm the absence of the Archean crust under the larger part of the region. New data suggests that the Svecofennian province of the Baltic shield extends farther to the south to the boundary with the Osnitsk-Mikashevichi belt. The crustal structure in this part of the East European platform, however, differs considerably from the Svecofennides of the Baltic shield by the unique alternation of its metamorphic belts. This feature demonstrates the specific geodynamic conditions during the formation of the Paleoproterozoic crust in the Baltic area and Belarus.

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REFERENCES

Aksamentova, N.V. and Naidenkov, I.V., Formation Stages of the Crystalline Basement Structure in the Western Part of the Russian Plate, *Geologiya i Perspektivy Rudonosnosti Fundamenta Drevnikh Platform* (Geology and the Prospects of Ore Potential of the Basement of Ancient Platforms), Leningrad: Nauka, 1987, pp. 162 - 171.

Aksamentova, N.V. and Naidenkov, I.V., *Geologicheskaya Karta Kristallicheskogo Fundamenta Belarusi i Sopredel'nykh Territorii, Masshtab 1 : 1 000 000* (The Geological Map of the Crystalline Basement of Belarus and the Adjoining Territories, Scale 1 : 1 000 000), Minsk: Inst. Geochim. Geofiz., Akad. Nauk Belarusi, 1990.

Aksamentova, N.V. and Naidenkov, I.V., *Ob'yasnitel'naya Zapiska k Geologicheskoi Karte Fundamenta Belarusi i Sopredel'nykh Territorii Masshtaba 1 : 1 000 000* (Explanatory Note to the Geological Map of the Basement of Belarus and the Adjoining Territories, Scale 1 : 1 000 000), Minsk: Inst. Geochim. and Geofiz., Akad. Nauk Belarusi, 1991.

Aksamentova, N.V., Naidenkov, I.V., Pap, A.M., and Il'kevich, G.I., The Early Precambrian of Belarus (Stratigraphy and Correlation), *Geol. Zh.*, 1991, no. 4, pp. 107 - 114.

Aksamentova, N.V., Dankevich, I.V., and Naidenkov, I.V., Deep Structure of the Belarussian-Baltic Granulite Belt, *Dokl. Akad. Nauk Belarusi*, 1994, vol. 38, no. 2, pp. 93 - 98.

Aksamentova, N.V., Arkhipova, A.A., Koshevenko, M.K., and Naidenkov, I.V., Rock Composition in the Gneiss Complex of the Crystalline Basement of the Pripyat' Granulite Belt, *Dokl. Akad. Nauk BSSR*, 1977, no. 7, pp. 618 - 621.

Arkhipova, A.A., The Osmolov Complex of the Archean Orthoclase-Plagioclase Granitoids of the Belarussian Massif, *Dokl. Akad. Nauk BSSR*, 1984, vol. 28, no. 8, pp. 744 - 747.

Bibikova, E.V., Kirnozova, T.I., and Makarov, V.A., The Age of Granites from the Belarussian Massif, *Metody Izotopnoi Geologii, Vsesoyuznyi Simpozium*, Methods of Isotope Geology, All-Union Symp., Moscow: Inst. Geokhim. Analit. Khim., 1982, pp. 52 - 53.

Bibikova, E.V., Kirnozova, T.I., Naidenkov, I.V., *et al.*, Isotopic Age of the Early Precambrian Okolovo Suite in Belarus, *Dokl. Ross. Akad. Nauk*, 1991, vol. 325, no. 4, pp. 803 - 807.

Bibikova, E.V., Kirnozova, T.I., Popova, L.P., *et al.*, The U-Pb Age and Correlation of Magmatic Formations of the Granulite and Amphibolite Complexes in the East European Platform, the Volga-Urals Region, *Stratigr. Geol. Korrel.*, 1994, no. 3, pp. 3 - 7.

Bogdanova, S.V., *Zemnaya Kora Russkoi Plity v Rannem Dokembrii* (The Earth's Crust of the Russian Plate during the Early Precambrian), Moscow: Nauka, 1986.

Bogdanova, S.V., Segments of the East European Craton, *EUROPROBE Symp., Jablonna 1991*, Gee, D.G. and Beckholmen, M., Eds., European Science Foundation – Polish Acad. Sci., 1993, pp. 33 - 38.

Claesson, S., Nd-Isotope Data on 1.9 - 1.2 Ga Old Basic Rocks and Metasediments from the Bothnian Basin, Central Sweden, *Precambrian Res.*, 1987, vol. 35, pp. 115 - 126.

DePaolo, D.J., Neodimium Isotopes in the Colorado Front Range and Crust-Mantle Evolution in the Proterozoic, *Nature*, 1981, vol. 291, pp. 193 - 196.

Geological Atlas of Crystalline Basement in Polish Part of East European Platform, Kubiski, S. and Ryka, W., Eds., Warszawa: Ins. Wyd. Geol., 1982.

Geologiya, Petrologiya i Metallogeniya Kristallicheskikh Obrazovanii Vostochno-Evropeiskoi Platformy (Geology, Petrology and Metallogeny of the Crystalline Formations in the East European Platform), Moscow: Nedra, 1976.

Geologiya i Perspektivy Rudonosnosti Fundamenta Drevnikh Platform (Geology and Ore Potential of the Basement of Ancient Platforms), Leningrad: Nauka, 1987.

Gorbatschev, R. and Bogdanova, S., The Baltic Shield and the Precambrian Basement Along the Tornquist Zone, *EUROPROBE Symp., Jablonna 1991*, Gee, D.G. and Beckholmen, M., Eds., European Science Foundation – Polish Acad. Sci., 1993a, pp. 73 - 79.

Gorbatschev, R. and Bogdanova, S., Frontiers in the Baltic Shield, *Precambrian Res.*, 1993b, vol. 64, pp. 3 - 22.

Huhma, H., Nd-Isotopic Composition and Age of Proterozoic Basalts from Northern Finland, (Abstract), *Terra Cognita*, 1984, vol. 4, p. 192.

Huhma, H., Claesson, S., Kinny, P.D., and Williams, I.S., The Growth of Early Proterozoic Crust; New Evidence from Svecofennian Detrital Zircons, *Terra Nova*, 1991, vol. 3, pp. 175 - 179.

Jacobsen, S.B. and Wasserburg, G.J., Interpretation of Nd, Sr and Pb Isotope Data from Archaean Migmatites of Lofonten-Vesteralen, Norway, *Earth Planet. Sci. Lett.*, 1978, vol. 41, no. 3, pp. 245 - 253.

Khvorova, G.P. and Utingof, I.M., The Northwestern Region, *Metamorfizm Ukrainskogo Shchita* (Metamorphism of the Ukrainian Shield), Kiev: Naukova Dumka, 1982, pp. 50 - 68.

Kornilov, N.A., Vetrennikov, V.V., Motuza, G., and Petersil'e, V., The Belarussian-Baltic Region, *Dokembriiskie Zhelezisto-Kremnistye Formatsii Evropeiskoi Chasti SSSR* (Precambrian Ferruginous-Siliceous Formations of the European Part of the USSR), Kiev: Naukova Dumka, 1988, pp. 108 - 122.

Krogh, T., A Low Contamination Method for Hydrothermal Decomposition of Zircons and Extraction of U and Pb for Isotopic Age Determination, *Geochim. Cosmochim. Acta*, 1973, vol. 37, no. 3, pp. 485 - 495.

Ludwig, K.R., ISOPLOT-Program, Open File Rep. 91, *U.S. Geol. Surv.*, 1991.

Mansfeld, J., Claesson, S., Sundblad, K., and Motuza, G., The Precambrian Crust Southwest of the Baltic Sea, *Terra Nova*, 1993, vol. 5., Abstract Supplement no. 1, p. 318.

Makhnach, A.S., Dominikovskii, G.G., Pasyukevich, V.I., *et al.*, *Zhelezorudnye Formatsii Belarusi* (Ferrous Ore Formations of Belarussia), Minsk: Nauka i Tekhnika, 1974.

Metamorficheskie Kompleksy Fundamenta Russkoi Plity (Metamorphic Complexes of the Russian Plate Basement), Leningrad: Nauka, 1978.

Mezhdunarodnaya Tektonicheskaya Karta Evropy i Smezhnykh Oblastei, Masshtab 1 : 2 500 000 (International Tectonic Map of Europe and the Adjoining Areas, Scale 1 : 2 500 000), Peive, A.V., Bogdanova, A.A., and Khain, V.E., Eds., Moscow: Akad. Nauk, 1981, 2nd ed.

Naidenkov, I.V. and Aksamentova, N.N., A Comparative Description of Early Precambrian Mafic Granulites and Metagabbroids of the Belarussian Massif, *Geol. Zh.*, 1983, no. 4, pp. 60 - 72.

Osnovnye Problemy Geologicheskogo Stroeniya Russkoi Plity (Basic Problems of Ecological Structure of the Russian Plate), Leningrad: Nauka, 1979.

Pap, A.M., *Endogennye i Ekzogennye Protsessy v Dokembrii: Rezul'taty Izucheniya Kristallicheskogo Fundamenta Belorussii* (Endogenic and Exogenic Processes in Precambrian: Results of a Study of the Crystalline Basement in Belarussia), Minsk: Nauka i Tekhnika, 1992.

Precambrian Basement of the Gulf of Finland and Surrounding Area, 1 : 1 000 000, *Geol. Surv. of Finl.*, 1994.

Puura, V. and Huhma, H., Palaeoproterozoic Age of the East Baltic Granulite Crust, *Precambrian Res.*, 1993, vol. 64, pp. 289 - 294.

Ryka, W., Precambrian Evolution of the East European Platform in Poland, *Bull. Inst. Geol. 347: Geology of Poland*, 1984, vol. VI, pp. 17 - 28.

Schatsky, N.S., On the Problem of the Age of Fold Basement of the Russian Platform, *Sov. Geol.*, 1940, no. 10, pp. 3 - 11.

Schatsky, N.S., Basic Features of the Structure and Development of East European Platform, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1946, no. 1, pp. 5 - 62.

Schatsky, N.S. and Bogdanov, A.A., Comments on the International Tectonic Map of Europe, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1961, no. 4, pp. 3 - 25.

Shcherbak, N.P., Pap, A.M., Bartnitskii, E.N., and Zayats, A.P., The Uranium-Lead Age of Granitoids of Belarussia, *Dokl. Akad. Nauk BSSR*, 1990, vol. 34, no. 8, pp. 740 - 743.

Shcherbak, N.P., Precambrian Subdivisions of the Ukrainian Shield as Referred to the Soviet and International Stratigraphic Scales, *Geol. Zh.*, 1991, no. 4, pp. 3 - 9.

Sobotovich, E.V., Pap, A.M., Ts'on', O.V., and Slupitskii, Yu.A., The Age of Crystalline Schists in Northwestern Belarussia, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1976, no. 9, pp. 42 - 47.

Stacey, J.S. and Kramers, J.D., Approximation of Terrestrial Lead Isotope Evolution by a Two-Stage Model, *Earth Planet. Sci. Lett.*, 1975, vol. 26, no. 2, pp. 207 - 221.

Steiger, R.H. and Jager, E., Subcommission on Geochronology: Convention on the Use of Decay Constants in Geo- and Cosmochronology, *Earth Planet. Sci. Lett.*, 1976, vol. 36, no. 3, pp. 359 - 362.

Sveshnikov, K.A., Sukhorukov, Yu.T., and Sherment, E.M., Anorogenic Granitoid Magmatism and Related Mineralization in the Ukrainian Shield, Abstract 29, *Int. Geol. Congr., Kyoto*, 1992, vol. 2, p. 563.

Van der Laan, S.R. and Wyllie, P.J., Constraints on Archaean Trondhjemite Gneisses from Hydrous Crystallization Experiments on Nuk Gneiss at 10 - 17 kbar, *J. Geol.*, 1992, vol. 100, pp. 57 - 68.

Wasserburg, G.J., Jacobsen, S.B., DePaolo, D.J., McCalloch, M.T. and Wen, T., Precise Determination of Sm/Nd Ratios, Sm, Nd Isotopic Abundances in Standard Solutions, *Geochim. Cosmochim. Acta.*, 1981, vol. 45, pp. 2311 - 2323.

Stratigraphy and Geological Correlation, Vol. 3, No. 6, 1995, pp. 602 - 620. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 3, No. 6, 1995, pp. 79 - 99.
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Development of the Riphean Carbonate Platform and Distribution of Silicified Microfossils: The Sukhaya Tunguska Formation, Turukhansk Uplift, Siberia

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Abstract – The limestones and dolomites of the Sukhaya Tunguska Formation, which are referred to the Middle-Upper Riphean boundary horizons (the isochron Pb-Pb age 1017 ± 91 Ma), are subdivided into five units composing two subformations. The silicified microfossils known predominantly from the upper subformation are mainly represented by the following taxa: (1) morphologically simple filamentous and coccoidal microfossils of genera *Siphonophycus, Gloeodiniopsis, Eosynechococcus, Eoentophysalis*, and others, which are the remnants of cyanobacteria of a wide stratigraphic range, and (2) remnants of a specific stalked cyanobacterium *Polybessurus bipartitus* unknown in the deposits below the upper part of the Middle Riphean. In addition, single remnants of supposed acanthomorphic acritarchs cf. *Trachyhystrichosphaera* were found in one site in the lower subformation. The facies reconstructions for each unit of the formation show that the Sukhaya Tunguska deposits form a continuous shallowing-up succession deposited in the poorly differentiated carbonate platform dipping gently northwestward. There were two stages in the platform development corresponding approximately to two Sukhaya Tunguska subformations. The early stage was during the high sea level stand and resulted in predominantly open-marine environments varying laterally. The late stage corresponded to the low sea level stand and uniform landscape in the upper subtidal zone and, at the end of the stage, in the intertidal zone. Most of the early diagenetic fossiliferous cherts are confined to the shallow-water and supershallow-water sediments of the late stage. The relatively deep-water deposits of the early stage reveal selective silicification rarely conserving microfossil remnants. The paleofacies reconstructions for the fossiliferous strata based on sedimentological records are concordant with results of the actualistic interpretation of paleoecological settings of certain microfossil morphotypes.

Key words: *Riphean, Proterozoic, carbonate platform, microfossils, stromatolites, cyanobacteria, facies, ecological distribution, paleoenvironments*

One of the main recent directions in Precambrian paleontology is oriented toward the study of the distribution of ecologically different microfossil assemblages in the basinal sediments. In addition to purely paleoecological interest, this direction is of great biostratigraphic significance because different facial settings appeared to be inhabited by taxonomically different assemblages differing in rates of morphological evolution and, subsequently, in stratigraphic potential.

In most publications, the paleoecological peculiarities of ancient microorganisms were inferred mainly from the direct comparison of ancient and modern microbiota without detailed sedimentological analysis of fossiliferous deposits (Hofmann, 1976; Knoll and Golubic, 1979; Knoll, 1984; Sergeev, 1992; and others). On the other hand, available reconstructions of Precambrian basins usually ignore paleobiological records left by microorganisms which inhabited there, although these dwellers are fine indicators of the paleoenvironments and active contributors to sedimentation and facies formation. It is evident that both approaches, the paleobiological and sedimentological, should complement each other both in reconstructing sedimentary facies of paleobasins and in the ecological analysis of the Precambrian biotas. First attempts to combine these approaches for deciphering life environments of organic-walled (Veis and Semikhatov, 1989; Vidal and Nystuen, 1990; Veis and Petrov, 1994) and mineralized (Knoll *et al.*, 1991; Fairchild *et al.*, 1991) Precambrian microbiotas proved the effectiveness of such a synthesis. This article is a further step in this direction. The focus of our investigations was the Riphean Sukhaya Tunguska Formation, Turukhansk uplift, Siberia (Fig. 1), which demonstrates the vertical and lateral distinctions of paleoenvironments, and contains abundant silicified microfossils in its upper part.

Silicified microfossils of the Sukhaya Tunguska Formation were discovered by Schopf in thin sections of B.B. Nazarov (Schopf *et al.*, 1977) and were described afterwards by Mendelson and Schopf (1982) based on these limited materials. Further investigations of Golovenok and Belova (1992, 1993) showed the

wider geographic distribution and more diverse composition of the Sukhaya Tunguska microfossils. These authors somewhat revised previously identified taxa and outlined their lateral and vertical changes. Our materials allow us to specify the structure of the Sukhaya Tunguska Formation, reconstruct the history of its formation, interprete the paleoenvironments, better analyze the composition of silicified microfossils, and define the ecological confinement of their individual representatives. The composition of the Sukhaya Tunguska microbiota and related taxonomic problems will be analyzed in detail elsewhere. The present article only deals with the taxonomy of entophysalidacean cyanobacteria, whose taxonomic affinity is of principal significance in deciphering facial environments. The presented materials were obtained during our studies of all Sukhaya Tunguska sections exposed in the Turukhansk uplift (Fig. 1).

STRUCTURE OF THE SECTIONS, AGE AND FACIAL CHARACTERISTICS OF THE SUKHAYA TUNGUSKA FORMATION

The Sukhaya Tunguska Formation composes limestones and dolomites 560 - 680 m thick, which enclose lenses and interbeds of black cherts confined mainly to the upper part of the succession. The formation is separated from the overlying Derevnya Formation by a regional hiatus, whereas downward it grades into the limestones of the Linok Formation, thus completing a large-scale sedimentational cycle. The cycle includes three formations: the siliciclastic Bezymyannyi Formation constituting the apparent base of the Turukhansk Riphean, and carbonate Linok and Sukhaya Tunguska formations above, all suggesting the paleobasinal evolution from a relatively deep-water state during the Bezymyannyi and Linok time to a progressively shallowing state during the Sukhaya Tunguska time (Petrov, 1993a, 1993b; Veis and Petrov, 1994).

At present, the age of the Bezymyannyi to Sukhaya Tunguska interval is interpreted ambiguously. These deposits are referred either to the upper part of the Middle Riphean or to the lower part of the Upper Riphean (for discussion and bibliography see Semikhatov and Serebryakov, 1983; Komar, 1990; Gorokhov *et al.*, 1995). In previous publications, we were of the former opinion because the abundant acanthomorphic acritarchs of the genus *Trachyhystrichosphaera*, the indisputable indicators of the Late Riphean age, appear only in the post-Sukhaya Tunguska deposits of Siberia, simultaneously with the important changes in stromatolite composition (for review and bibliography see Semikhatov, 1991). In light of recent data (Sergeev, 1992; Knoll and Sergeev, 1995), the composition of the Bezymyannyi organic-walled microfossils does not contradict such a conclusion, although some researchers used this composition as a main argument to substantiate the Late Riphean age of the rocks (Veis and Vorob'eva, 1993). The occurrence of scarce, presumably acanthomorphic acritarches cf. *Trachyhystrichosphaera* in the Sukhaya Tunguska Formation may also change the idea on its Middle Riphean age. The Pb-Pb isochron age of the carbonate deposits of the formation is 1017 ± 91 Ma (Ovchinnikova *et al.*, 1994).

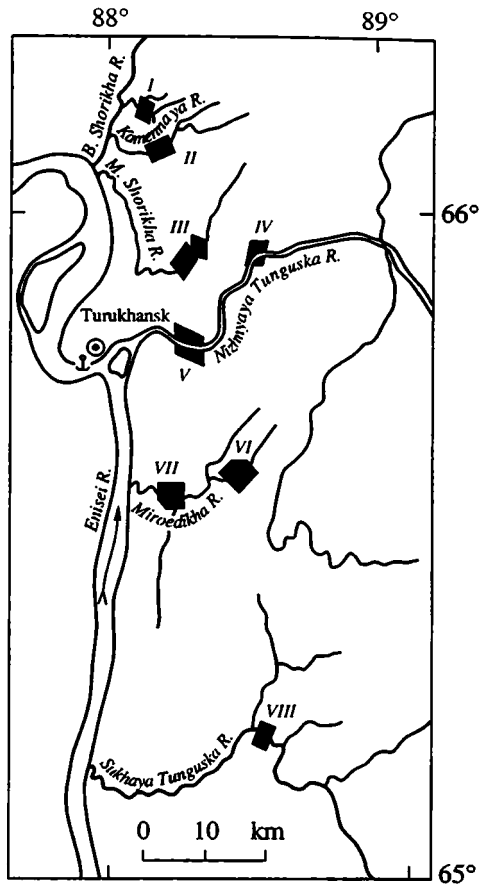

Fig. 1. Location of the studied sections of the Sukhaya Tunguska Formation.

I - VIII – sections: *I* – Nadporozhnaya River, *II* – Kamennaya River, *III* – Malaya Shorikha River, middle stream, *IV* – Nizhnyaya Tunguska River downstream of the Gremyachii Creek mouth, *V* – Nizhnyaya Tunguska River, *VI* – Miroedikha Vtoraya River, *VII* – Miroedikha River, lower stream, *VIII* – Sukhaya Tunguska River upstream of the Tabornaya River mouth.

In the recent structure of the Turukhansk uplift, the Sukhaya Tunguska Formation is a constituent of two submeridional tectonic plates thrust eastward and dipping in the west direction at an angle of 10° - 40°. The lower boundary of the formation is conventional and assigned to different levels. We draw this boundary at the level of transition from the light-colored fine-bedded limestones of the Linok Formation to darker (up to black) carbonate deposits. At least in some sections, this boundary also separates deposits with differing values of $\delta^{13}C$ (Knoll *et al.*, 1995).

The Sukhaya Tunguska Formation can be subdivided into two subformations (Dragunov, 1963).

The lower subformation is represented by dark gray (up to black) carbonate deposits dominated by limestones in the south of the region and dolomites in the north; the upper subformation is composed of light gray dolomites with chert nodules of various form.

The lower subformation comprises three units grading into each other.

In the southern and central parts of the region *the lower unit* (from 120 to 130 m) is composed of dark gray and black pelitomorphic limestones divisible into two facies, the pelitomorphic and clastic varieties.

The pelitomorphic limestones prevalent in the unit show fine horizontal bedding, usually poorly pronounced, and form relatively thick (10 - 12 m) uniform packages. Some beds have an almost massive structure. The limestones are mostly represented by calcilutite of an isocrystalline structure (crystaillites are not more than 0.01 mm in size). Their permanent components are scattered pellets of silt size, whose distribution shows some stratification and local graded bedding. In the upper part of the unit there are some isolated laminae of calcisiltites and calcarenites. In the laminae, the sand-size grains (0.06 - 0.4 mm) consist mainly of rounded or, less frequently, slightly flattened oolites with well-crystallized central zones, whereas the silt-size grains are composed only of isotropic micrite. The laminae do not show erosional surfaces at the base and grade upward into the calcilutite mass. They usually display the syneresis cracks strongly deforming the lamination. Present mainly in the upper part of the unit, the cracks are filled with fine-crystalline gray calcite or light coarse-crystalline dolomite. The limestones include an insignificant amount of scattered fine (less than 0.05 mm) framboidal pyrite crystals and abundant rounded, oval, or dumbbell-shaped concretions of dark gray cherts, up to 20 cm in diameter. In the concretions, silica either homogeneously replaces the carbonate material, locally almost completely, or forms thin (3 - 5 mm) outer rims.

The clastic limestones can be conventionally classified into fine- and coarse-grained types. The first type is represented by gravel and fine-pebble flakestones constituting lenses and interbeds from 1 to 20 cm in thickness, which have horizontal or, less frequently, cross bedding with an amplitude up to 5 cm. The bedding is usually accompanied by a series of small-scale local erosional surfaces. The clasts consist of calcilutite indistinguishable from the above-varieties, while the matrix is dominated by detrital calcarenites. The fine clasts are more isometric and better rounded than the coarse ones, which have the form of thin narrow plates. The flattened clast form suggests them to be the result of syndepositional brecciation of cemented carbonate laminae. Noticeable amounts of the described flakestones appear in the middle and upper parts of the unit in the south of the region.

Coarse clastic limestones can be observed in the upper part of the unit in the extreme southern section at the Sukhaya Tunguska River and, in insignificant amount, in the basal horizons of the unit in the center of the region. Their usually poorly rounded clasts represent the flat fragments (flakes) of brecciated thin beds of thin-laminated limestones. The flake sizes vary over a wide range; the largest of them are 8 - 10 mm thick and 8 - 15 cm across. The coarse clastic flakestones with compact wackestone texture form beds which are 5 - 50 cm in thickness. The flakes are usually chaotically or subhorizontally oriented; less frequently, they show a unidirectional cross bedding with an amplitude up to 50 cm. In some cases, they are oriented along the coarse cross-wavy bedding. The amount of these rocks and the size of the flakes increase upward in the section of the Sukhaya Tunguska River (Fig. 2).

In the north of the region, at the Kamennaya River, the lower part of the unit is composed of pelitomorphic limestones with some horizons of fine clastic and rare coarse clastic rock types, while the upper part is comprised of mostly granular (evidently crystalline) dolomites and subordinate pelitomorphic limestones. The dolomites compose the whole section of the unit exposed along the Nadporozhnaya River. Judging by the relic textures, they are recrystallized pelitomorphic and fine clastic limestones.

Thus, against the background of the consistent thickness of the unit (120 - 130 m), the amount of clastic rocks and size of the characteristic clasts increase up-section and decrease abruptly upon passing from the southern to northern sections.

The middle unit of the lower subformation is represented by associated deposits of three facial types: (1) dark gray or dark brown pelitomorphic limestones (or crystalline dolomites) with thin horizontal lamination; (2) calcarenites showing coarse horizontal, cross and cross-wavy lamination; (3) stromatolitic limestones (in the southern and central parts of the region) and dolomites (in the northern part) and related carbonate sandstones. The unit thickness increases from 20 m at the Sukhaya Tunguska River to 30 m at the Nizhnyaya Tunguska River; however further northward it reduces down to 4 - 6 m at the Kamennaya River. There are no exposed deposits of the unit in the extreme northern sections of the formation at the Nadporozhnaya River.

The pelitomorphic limestones of the middle unit are similar to their analogue from the lower unit in external appearance and texture, but differ in their abundant syneresis cracks (molar-tooth structures) and finer crystalline size (up to micritic). Calcarenites consist of rounded grains of isotropic micrite, fine to coarse sand-size grains and less frequent oolites. The grains are set into the fine-grained crystalline matrix. These rocks usually show gentle (dipping angle less than 10°) cross and cross-wavy lamination; steep unidirectional trough cross lamination occurs less frequently; in some places distinct ripple lamination can be observed. The calcarenites constitute extensive beds, 0.2 - 0.5 m thick, filling the depressions between stromatolitic bioherms. In the

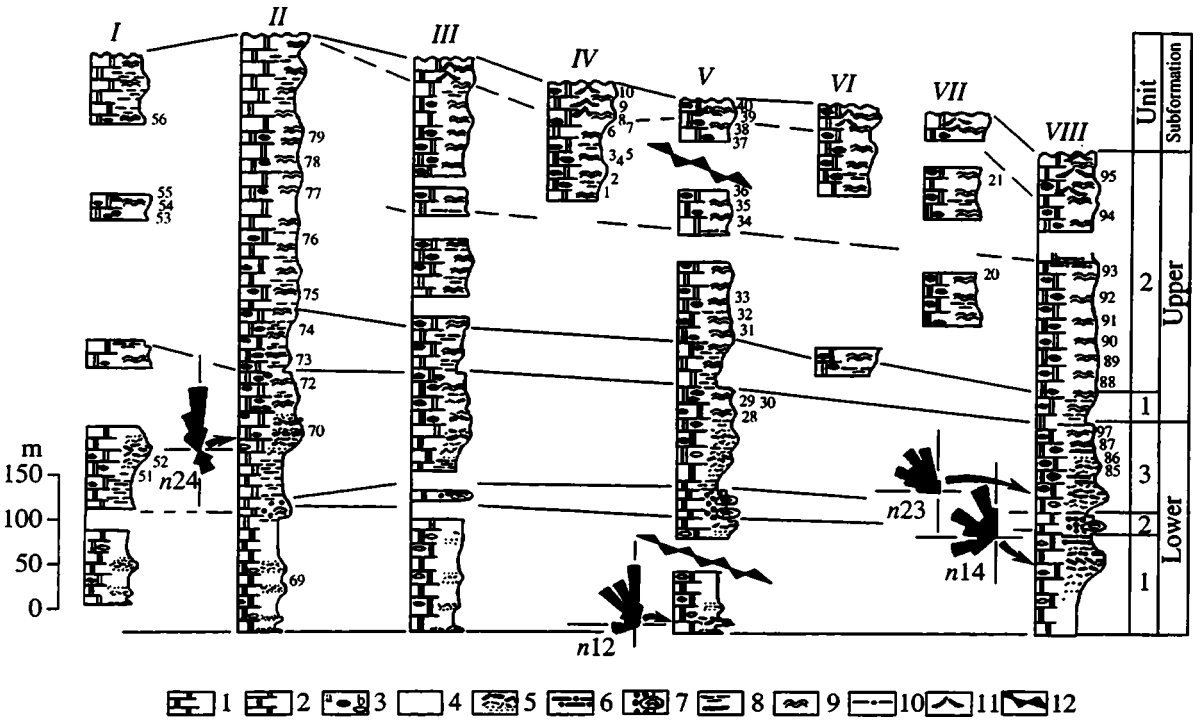

Fig. 2. Sections of the Sukhaya Tunguska Formation.

1 – limestones; 2 – dolomites; 3 – cherts (a – early diagenetic, b – late diagenetic); 4 - 10 – facial associations: 4 – pelitomorphic limestones (dolomites), 5 – clastic limestones (dolomites), 6 – pelitomorphic and clastic limestones of the upper part of the lower unit, 7 – sandy-stromatolitic association, 8 – horizontal-bedded laminites and dark gray parallel-laminated dolomites, 9 – wave-laminated dolomites, 10 – sandy dolomites; 11 – tepee structures 12 – upthrusts and brecciation zones. Roman numbers for sections (see Fig. 1), arabian numbers for position of fossiliferous samples.

southern and central parts of the region, near the unit's top, calcarenites are expelled by pelitomorphic limestones. In the north, the sharply reduced abundance of clastic carbonates is recorded throughout the unit.

Flat, elongated or isometric bioherms of stromatolites are confined to some horizons of the middle part of the unit. There are two horizons at the Sukhaya Tunguska River and five horizons at the Nizhnyaya Tunguska River, downstream of the Strel'nye Gory. The first and fifth horizons include large elongated bioherms, up to 3 to 4 m in thickness. In other horizons, bioherms are smaller, isometric or slightly elongated, and up to 2 to 2.5 m thick. In the Kamennaya River basin, small (30 - 50 cm thick) scattered bioherms are confined to the 4 to 6-m-thick package. The character of the lower boundary of stromatolite buildups changes in the same direction. To the south of the Kamennaya River, they rest on the highly dissected (up to 1 m) erosional surface of underlying deposits (Serebryakov, 1975, Figs. 20 and 34), whereas in the Kamennaya River basin, the underlying surface is without erosion marks. The synoptic relief of large bioherms was of variable height from dozens of centimeters, to 1 - 1.5 m locally. This relief is buried under the cross-wavy and hummocky laminated calcarenites, or sealed by dark gray pelitomorphic limestones. The calcarenites filling the interbiohermal spaces clearly show hummocky lamination with an amplitude of 30 - 40 cm (the Malaya Shorikha River).

Growth of stromatolite buildups began with stratiform *Stratifera* and was soon replaced by columnar *Baicalia prima* Semikh. in the inner parts of large bioherms, and by *Tungussia nodosa* Semikh. in the peripheral parts or small bioherms (Semikhatov, 1962). At the tops of some bioherms, columnar structures are replaced by columnar-stratiform and stratiform structures. All the stromatolites are of a uniform microstructure. The upper biohermal boundary is usually conformable or, less frequently, erosional, truncating the columns of *Baicalia* and *Tungussia*.

The changes in the middle unit are expressed in the decreasing occurance of calcarenites up-section and from southern localities northward. The abundance of stromatolites decreases from the central part of the region (the Nizhnyaya Tunguska River) southward, and especially northward.

The upper unit of the lower subformation comprises diverse facies associations, including the most coarse clastic deposits spread throughout the region. In addition, the unit includes dolomitized fine-grained crystalline limestones and recrystallized original (early diagenetic) dolomites, more precisely, dolomicrites and dolo-

lutites. The dolomitization affected the whole unit in the north of the region, a majority of its upper part in the center, and the uppermost horizons in the south (Fig. 3). The gradation from limestones to dolomites in the southern (the Sukhaya Tunguska River) and central (the Nizhnyaya Tunguska River) parts of the region is associated with the appearance of abundant dark gray and black cherts containing well-preserved microfossils. The unit thickness increases from 100 m at the Sukhaya Tunguska River to 120 - 130 m in the central part and 150 m in the north of the region.

The unit comprises three facial associations: horizontally bedded laminites, clastic carbonates of a wide granulometric spectrum, and wave-laminated dolomites with black chert interbeds.

The association of the horizontal bedded laminites is represented by dark gray fine-crystalline micritic limestones and crystalline dolomites. The laminites differ from the underlying limestone horizons in their more distinct, fine (0.1 to 1 cm) parallel ribbon bedding, and in more abundant syneresis cracks sometimes composing up to 50% of the rock volume. The association consists of three alternating facial types composing packages, each 0.5 - 5 m thick, where the relative role of each type can vary over a wide range (Fig. 3). The following are the three facial types:

(1) Pelite-siltite laminites variable in composition from calcilutite to fine-grained sludge calcarenites. They constitute relatively thick (5 - 10 mm) individual laminae with microerosional surfaces, local indistinct graded structures, and sparse cross lamination at the sole. The sludge is composed of fragments of thin micritic crusts (hyaloflakes), and peloidal sand-size grains sometimes represented by oolites with a crystalline central zone. The described laminites are purely mechanogenic carbonate deposits accumulated in quiet-water environments. (2) Fine-striated laminites represented by flat and horizontally laminated calcilutites, dololutites, and fine-crystalline dolomites. The striation patterns are formed by the frequent (intervals of 0.1 - 0.5 mm) micritic microlaminae and/or by dark films enriched in organic matter. Many films show the crinckled lamination with distinct upper and diffuse lower boundaries and can be considered as possible relics of cyanobacterial mats. The lamination is usually deformed by a network of syneresis cracks, which triggered locally the development of intrabed post-sedimentary breccias. The fine-striated laminites correspond to the finest carbonate muds cemented partly (along microbeding) with syngenetically lithified microlaminae (micrites) and/or with the residual organic matter of benthic microassemblages. (3) Micritic laminites representing the isotropic or microclotted deposits, which frequently have lamination similar to that of stromatolites *Malginella zipandica* Kom. (Komar *et al.*, 1973). Locally, the deposits show the *Frutexites*-like microstructures (Maslov, 1960) with patterns of isolated thalluses or extended bands. It should be noted that most of the observed *Malginella*-like structures are of diagenetic origin (dissolution–fragmentation) in this case. The micritic laminites are syngenetically lithified sediments, and served as the source of all clastic deposits described below.

The association of clastic carbonates of the upper unit consists of light gray and gray gravel and flat-pebble (clasts up to 20 cm long) flakestones constituting separate beds, 5 - 20 cm thick, and local thin packages, up to 1.5 to 2 m thick. The average size of the clasts is proportional to the thickness of the breccia beds, with the thickest usually displaying the coarse unidirectional cross lamination. As a rule, the deposits have coarse graded bedding, including that of the reverse type observed at the bases of some coarse clastic beds. In addition, some varieties of these deposits show an imbricated cross and subvertical arrangement of flat pebbles similar in size, which form structural patterns similar to "stone rosettes" (Dionne, 1971). The thin (up to 10 cm) interbeds of the fine clastic flakestones alternating with the horizontally bedded laminites produce a characteristic and stable paragenesis, and the coarse clastic flakestones usually form thicker uniform beds and packages.

The association of wave-laminated dolomites is represented by thick bedded (30 - 50 cm) deposits with noninherited gentle wavy lamination of an amplitude up to 2 to 4 cm. The light gray, gray and locally dark gray deposits include lenticular interbeds of dark gray and black cherts. The association comprises three closely related facial types.

(1) Cryptoalgal laminites consist of dolomicrite or apparently crystalline dolomite and have fine microwavy disharmonic lamination, which resembles the stromatolitic type. The microtextures are clotted or isotropic; the fenestrate textures occur in the crystalline rocks. (2) Granular dolomites (grainstones) are unsorted dolosiltites and dolarenites containing scattered gravel grains and flat small clasts (flakes) variously rounded. Generally, they are distinguishable from the above-described clastic carbonates in unsorted appearance of the clasts, although the coarse-grained fractions frequently demonstrate both normal and reverse graded bedding. All clastic grains are of dolomicrite composition and along with enclosing the dolomitic matrix are variously recrystallized. Usually the deposits have a gentle wavy lamination; the fine-grained varieties occasionally show the cross or cross-wavy lamination, and locally, the ripple lamination. The granular dolomites form thin lenses and interbeds alternating with the cryptoalgal laminites; infrequently they occur as independent thin beds and packages. (3) Flat-pebble breccias represent unsorted flat clastic wackestones with subhorizontally oriented clasts. The largest clasts, up to 20-cm long and usually isolated, are the virtually unremoved fragments of brecciated beds of the cryptoalgal laminites embedded in the surrounding fine-grained matrix. Frequently these fragments bear traces of syndepositional plastic defor-

mations. The flat-pebble breccias form thin beds and, less frequently uniform packages, 0.5 - 1.0 m thick. The whole facial association was formed under conditions of permanent wave activity.

There are certain trends in the time-and-space distribution of the facial associations of the upper unit (Fig. 3). In the southern sections, its lower and middle horizons are dominated by relatively coarse clastic flakestones. Northward, to the Nizhnyaya Tunguska River, the flakestone beds become much thinner, grading into finer rock varieties, and replacing up-section the micritic and fine-striated laminites. Along with these changes, a wedge of dark gray pelite-siltite and less frequent fine-striated laminites widening northward appear in the lower part of the unit. In the northern sections these deposits lose their original structural and textural features due to secondary dolomitization and recrystallization. The relics of structures and microstructures suggest the predominance of the pelite-siltite laminites there.

As for the upper horizons of the described unit, they are represented in the southern part of the region by a uniform package (30 m thick) of wave-laminated dolomites. Northward, the package increases in thickness up to 50 - 55 m and is wedged by thin interbeds of the fine-striated laminites and clastic carbonates. Below we shall see that the lower boundary of this package separates the two greatest facial complexes of the Sukhaya Tunguska Formation.

By passing from southern sections northward, the upper unit of the lower subformation demonstrates the reduced abundance of clastic components and increasing significance of sediments deposited in relatively quiet and deeper environments; the unit thickness tends to rise from 100 to 150 m, whereas the overall thickness of the lower subformation increases from 240 to 300 m in the same direction.

The Upper subformation is composed of light gray, gray and, at the lower part, dark gray clastic dolomites with frequent interbeds, lenses and concretions of cherts. This generally uniform succession is subdivided into two units.

The lower unit includes predominant dark gray, mostly crypto- and fine-grained, clastic, horizontal-laminated dolomites. The unit tends to increase in thickness from south northward from 30 to 70 m, and comprises two facial associations: the dark gray dolomites with either parallel or wavy lamination.

The first association is usually composed of recrystallized deposits (crystals up to 0.2 to 0.4 mm) and demonstrates thin horizontal lamination formed either by alternating nonrecrystallized fragments of micritic and microsparitic laminae, 0.1 - 0.5 mm thick, or by discontinuous films enriched in organic matter. The dolomites reveal abundant syneresis cracks, which are most widespread (locally up to 80% of rock volume) in the lower beds of the unit. Some beds are black in color and have a bituminous smell, although the organic matter content does not exceed 1%. The deposits commonly show the relic granular and thin clastic texture. The clasts are preserved as shadow peloidal particles of sand size or as coarser (up to 5 mm) elongated micritic granules, the well rounded lamina fragments. The described dolomites constitute packages varying in thickness from 1 to 20 m, including lenses and interbeds of black cherts. This association is similar to that of the horizontal-bedded laminites of the lower subformation, differing from it purely in dolomite composition, in abundance of thin bedded varieties with apparently visible crystalline texture, and in high content of organic matter. The characteristic features of the deposits indicate their accumulation mainly in quiet-water environments.

We described the association of wave-laminated dolomites in detail when considering the lower subformation. In the upper subformation the same association has: lighter color of rocks, wider distribution of dolomicrite (composing separate laminae with the isotropic microstructure), thicker bedding, and abundant lenses and interbeds of black cherts, 0.5 - 10 cm thick. Silicification affected every facial type here, dominating in the cryptoalgal laminites and avoiding the flat-pebble breccias. Silica completely replaces the carbonate material, conserving microstructures, which include microstromatolites or precipitates of submillimeter size. The frequent lenses and interbeds of cherts are also confined to the boundaries between the dolomite beds of the two associations. The wave-laminated dolomites form thin (2 - 4 m) packages or alternate (in 0.5 - 1 m interval) with the dark gray dolomites with parallel lamination. Up-section and laterally, from south northward (Fig. 2), this alternation exhibits the decreasing occurence of the first dolomite types. Unlike the association of horizontal-laminated dolomites, the considered one accumulated under permanently mobile but moderately active environments in a setting, where the generated coarse clasts were not transported far away.

The upper unit completing the section of the Sukhaya Tunguska Formation is uniform throughout the Turukhansk uplift. Its composition is dominated by the association of gray and light gray wave-laminated dolomites alternating with subordinate associations of sandy dolomites and dolomites with parallel lamination. The latter are distinguishable by their dark color and form separate horizons exposed along the unit base (mainly in the northern sections) and a thin package at the unit top exposed along the Kamennaya and Nadporozhnaya rivers. The wave-laminated dolomites of the upper unit include thin (1 - 5 cm) interbeds, lenses and small isometric concretions of black cherts decreasing in abundance up-section which is accompanied by a change in the chert color from black to light gray. In the upper part of the unit these dolomites enclose small (up to 5 to 7 cm high) domes of stratiform stromatolites.

The uppermost horizons of this unit in the southern and central sections are also distinguished by antiform

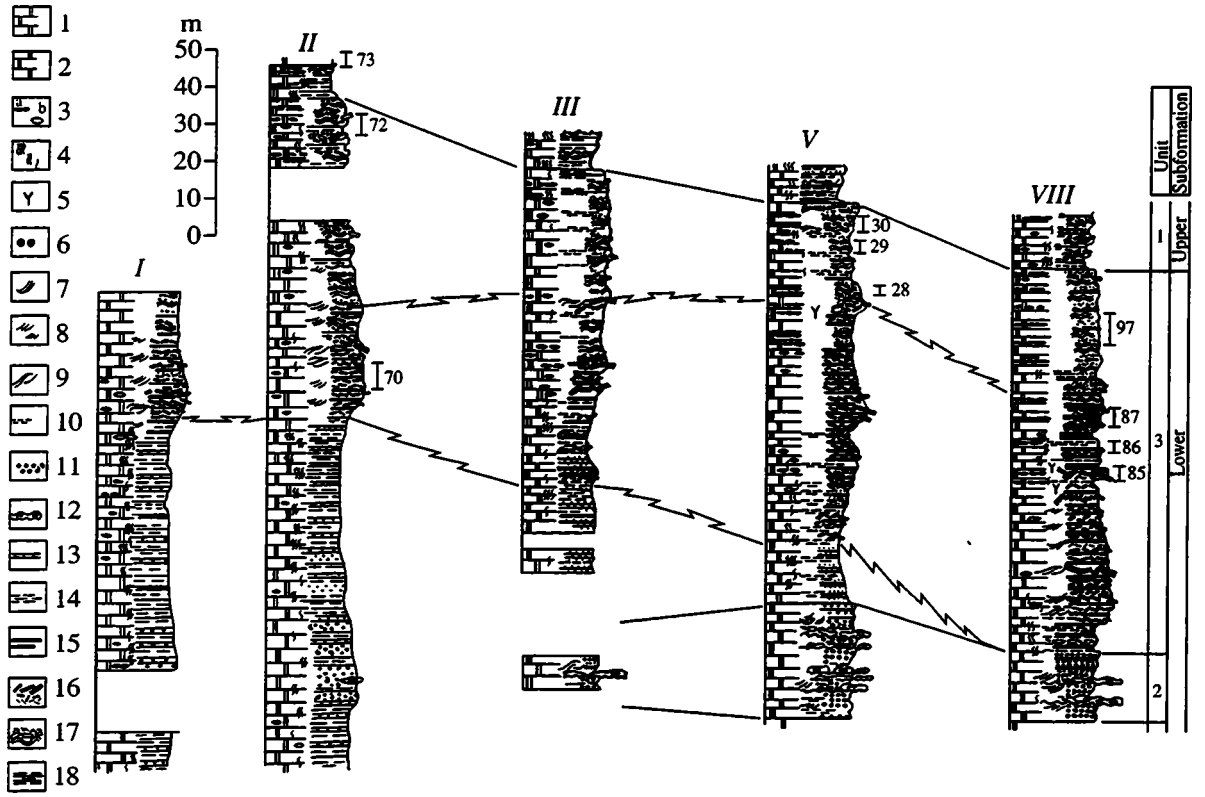

Fig. 3. Lithology and facies of the middle part of the Sukhaya Tunguska Formation.
1 – dolomites; 2 – limestones 3 – cherts (lenselike interbeds and concretions) (a – early diagenetic, b – late diagenetic); 4 – syneresis cracks; 5 – *Frutexites*-like microstructures; 6 – oolites; 7 – trough cross-lamination; 8 – flat-parallel cross-lamination; 9 – wavy cross-lamination; 10 - 14 – facial types: 10 – pelitomorphic limestones of the middle unit, 11 – calcarenites, 12 – stromatolitic bioherms, 13 – pelite-siltite laminites, 14 – fine-striated laminites; 15 – micritic laminites; 16 - 18 – facial associations: 16 – clastic carbonates, 17 – wave-laminated dolomites, 18 – dark gray parallel-laminated dolomites (arabian numbers for fossiliferous samples and the stratigraphic range of sampling).

structures, up to 15 cm high, and some of them are the characteristic tepee structures (Assereto and Kendall, 1977) indicative of the short-term emergence events. The thickness of the package with these structures decreases from 48 to 50 m at the Sukhaya Tunguska River to 18 to 20 m at the Malaya Shorikha River. There are no tepee structures noted farther north.

The association of sandy dolomites form thin (3 - 4 m) beds confined, probably, to a single stratigraphic level in the middle part of the unit. The deposits show thin (1 - 20 mm) gradational alternation of dolosiltite, dololutite, and fine-grained dolomitic sandstone, all having horizontal and gentle cross-wavy lamination, with interbeds (0.5 - 3 cm) of uniform dolomicrite or microsparite. These interbeds are commonly brecciated, and frequently were source rocks for sandy and rare gravel grains. At the Malaya Shorikha River, the dolomicrite interbeds show small erosional channels, 2 to 5 cm deep, and the sandstones contain rare grains of clastic quartz. At the Nizhnyaya Tunguska River, imprints of cubic halite (?) crystals with 0.3- to 1-mm-long facets were observed in the micrite-sparite matrix of the dolomitic sandstone. Up-section, the sandy deposits are abruptly replaced by horizontally laminated dololutite, and then by the cryptoalgal laminites and wavy laminated dolomites typical of the upper subformation.

The thickness of the upper unit increases in northern and northwestern directions from 270 to 310 m; the entire upper subformation changes in thickness from 300 to 380 m. The overall thickness of the formation rises in the same direction from a minimum of 530 - 540 m (the Sukhaya Tunguska River) to a maximum of 660 - 670 m (the Kamennaya River).

FACIAL SYSTEMS, PALEOENVIRONMENTS, AND HISTORY OF DEVELOPMENT OF THE SUKHAYA TUNGUSKA BASIN

The continuous succession of the Sukhaya Tunguska deposits was formed in the carbonate platform dipping gently northwestward. This can be inferred from the following facts: (1) we observed lateral continuity of all lithostratigraphic subdivisions of the formation and a successive thickness increase in northern and northwestern directions; (2) the paleocurrent distribution reconstructed by measuring the cross bedding and

dip of flat pebbles showed that modes of measurements are concentrated in the northwestern sectors of the diagrams (Fig. 2); (3) the abundance of sediments deposited in deeper settings increases in the northern and northwestern directions. The platform structure, which was inherited from the previous Bezymyannyi stage of the region development (Petrov, 1993b), seems to have corresponded to the tectonically stable period characterized by the low rate of differentiated movements and, likely, general subsidence. This evolutionary trend resulted in deposition of the shallowing-up succession of the entire Sukhaya Tunguska Formation. Against the background of this succession, there were some rearrangements of facial systems in the paleobasin, related either with outer factors (sea level oscillations and changes in subsidence rates) or with the internal features of the marine paleolandscape evolution.

The above data reveal two stages in the development of the Sukhaya Tunguska platform, which correspond to two facial complexes (Fig. 4). The boundary between these complexes lies within the upper unit of the lower subformation (below its upper package), and separates the rather variable complex of the early stage accumulated during the high sea level stand from the monotonous deposits of the late stage formed during the low sea level conditions.

The early stage is subdivided into three phases. The early phase (the lower unit) gave rise to the accumulation of pure and peloidal calcareous muds in the quiet environments below the storm wave base (the association of pelitomorphic limestones). In the southern part of the region only, these environments were modified in the second half of the phase by the appearance of relatively shallow settings within the active zone of gradient storm currents and, likely, above the storm wave base (the facial association of clastic limestones). All clastic components of these deposits were likely transported by suspension flows. The coarse clastic fractions were removed not far from areas of local erosion, whereas the fine clastics, including the mobilized sandy-silty material, formed extended aprons (Fig. 5a). The generally monotonous character of these deposits distinguishes them from the classical succession of distal tempestites (Aigner, 1985). The Sukhaya Tunguska pelitomorphic limestones of the lower unit are deprived of visible characteristic bed pairs produced by storm suspension processes; the graded bedding is expressed here only at the microlevel. But the boundary between the distal (pelite-siltite-sandy deposits) and proximal (flakestones) facies is very sharp. This suggests the low hydrodynamic energy of storm events in the Sukhaya Tunguska paleobasin distinguishing them from the processes typical of open marine basins.

Deposits of higher energy environments (the coarse clastic flakestones) observable in the upper part of the unit in the southern and central sections occur in the form of a progradation wedge migrating up the stratigraphic vertical to disappear from the unit at the right bank of the Nizhnyaya Tunguska River. In addition, there are also some thin clastic beds in the basal horizons of the unit in the southern and central part of the region (Fig. 5). The material composing all clastic deposits of the lower unit was transported northwestward (Fig. 2). Therefore, during the early phase, the hydrodynamically active zone of the platform should move toward the open basin.

Thus, the rise of the sea level during the early Sukhaya Tunguska time resulted in the migration of the outer facial zones of the platform toward the open basin. Simultaneously, a protected inner zone with exclusively quiet-water sedimentation developed in the southern part of the region. Accordingly, the basal horizons of the platform can be considered as a transgressive sedimentary complex overlain by the prograded shallowing succession formed during the stable and high sea level stand. The persistent thickness of the lower unit of the formation suggests the absence of differentiated movements of that time and the eustatic origin of the early Sukhaya Tunguska transgression.

The intermediate phase (the middle unit of the lower subformation) was distinguished by essential changes in the facial systems of the platform (Fig. 5). Characteristic of this phase were medium-scale (3 - 6 m) cycles which included such characteristic members as stromatolitic bioherms. Preceded by a distinct erosional surface, every cycle began with the deposition of stromatolite bodies and synchronous sandy sediments to be completed with accumulation of fine carbonate muds locally replaced up-section by sandy deposits. The erosional surfaces spread throughout southern and central parts of the region resulted from the underwater abrasion, as is evident from their relief and "floating" (detached) fragments of substratum occuring in the basal horizons of the overlying deposits. At the end of their formation they were elements of the hard ground. The formation of the hard ground, which served as a base for the stromatolitic buildups (Serebryakov, 1975), and associated mobile substratum (sands) were likely distinct factors of this phase, which lacked the flat-clastic carbonates which appeared in abundance under conditions of mechanically stratified substratum of the earlier and later evolutionary phases of the Sukhaya Tunguska platform.

The sandy sediments of the phase under discussion were affected by permanent wave activity, whereas the pelitomorphic limestones at the top level of bioherms evidently were accumulated in the local protected areas as syngenetically lithified carbonate crusts (remnants of cyanobacterial mats?) and fine carbonate muds binded by them. The overlying limestones of this facial type were presumably muddy-silty sediments spread over vast areas during the maximal rise of the sea level. Each cycle of the unit shows an asymmetric transgressive-regressive trend, and their stromatolitic bioherms were formed during the rapid rise of the sea level.

Thus, the sandy-stromatolitic association of the second phase of the platform development was formed as a result of a series of frequent sea level changes comparable in amplitudes with the cycles. The erosional surfaces at the cycle bases were hardly isochronous; in the southern direction they migrated up-section due to the general southward movement of the basinal hydrodynamic maximum and related migration of the sandy facies zone to the southern part of the region, toward the Sukhaya Tunguska River. The entire sandy-stromatolitic association represents a transgressive succession formed under the retrograde regime.

The third, terminal phase of development of the early Sukhaya Tunguska basin (the third unit of the lower subformation, excluding its upper package) was characterized by a more complicated facies pattern, although the positions of facies boundaries (Figs. 3 and 5) suggest that this phase inherited its main features from the first one. The sedimentary succession of this phase (as well as that of the first phase) represents a unidirectional trend of shallowing and demonstrates the migration of the shallow-water facial zone northward, toward the open basin. This inferrence is in accordance with the estimated paleocurrent directions (Fig. 2). During the third phase of the basinal development, the sedimentational environments changed in the following manner.

Settings with maximal storm energy marked by the thickest (up to 1 m) beds of coarse clastic flakestones were typical of the beginning of this phase in the extreme south of the region and migrated, with time, northward (Fig. 3). The migration of the facial zone with coarse clastic carbonates was accompanied by a noticeable energy decline of some events. This is evident from the decreasing thickness of the flakestone beds and lower amplitudes of cross lamination in the central and northern parts of the region, as well as from changes in the granulometric composition and structure of deposits showing the increased proportion of sandy-gravel fractions in the coarse clastic carbonates, finer clast sizes, better rounded medium-sized clasts, and amalgamation of adjacent beds. These changes suggest that the association of clastic carbonates in the northern part of the region was formed in coastal settings under the conditions of permanent wave activity and repeated storm events.

In the southern part of the region, the high-energy environments marked by the mentioned flakestone accumulation changed very abruptly into quiet-water conditions. The thin-striated and micritic laminites were deposited in the protected quiet-water areas (lagoons?), whereas associated flat-clastic deposits formed in the peritidal settings (Fig. 5c). The latter include horizons with an imbricated arrangement of rounded flat pebbles.

Thus, storm progradation was characteristic of the southern, proximal part of the platform at the very beginning of the third phase. Afterwards, the shallow-water environments spread rapidly over the entire platform. The transition from the environments of the differentiated "distal-proximal platform" to the laterally continuous pulsating shoal area was the turning point to the next stage of the history of the Sukhaya Tunguska.

This *late stage* of the development of the Sukhaya Tunguska platform comprises the upper package of the third unit of the lower subformation and the entire upper subformation, all deposited under conditions of low sea level stand (Fig. 5). Respective sediments are represented predominantly by two facial associations: the association of dark gray parallel laminated dolomites, and the association of wave-laminated dolomites, which formed in the shallowest water environments. This generally uniform succession exhibits two boundaries, which coincide with the bases of two units of the upper subformation and separate section intervals with different proportions of these associations and their facial types. Therefore, the late stage can be subdivided into three phases (Fig. 5).

The early phase (the upper package of the third unit of the lower subformation) completed the continuous trend of shallowing typical of the entire unit. This phase was characterized by the predominance of extreme shallow water settings, where the association of wavy laminated dolomites (granular and clastic deposits of various types) accumulated under permanently agitated environments. The possible importance of the role of biogenic carbonate sedimentation related to the activity of cyanobacterial assemblages during the formation of these deposits was mentioned above. Settings in the northern part of the region included subordinate quiet-water areas, where the fine carbonate muds (the association of dolomites with parallel lamination) accumulated. The first occurrence of early diagenetic cherts is confined to the deposits of this phase.

The intermediate phase (the lower unit of the upper subformation) corresponds to the sedimentation interval of the dominant association of dark gray dolomites showing parallel lamination and enriched in dispersed organic matter. These deposits were mostly formed in the permanently quiet subtidal environments of relatively vast but, probably, isolated areas of the platform (Fig. 5), which were represented by pools separated by extremely shallow areas of accumulation of wave-laminated dolomites. This interpretation follows from the lateral discontinuity of the units of the dark gray parallel-laminated dolomites replaced by the light wave-laminated dolomites over the distance of a few kilometers. With time, these pools decreased in size and their zone migrated toward the open basin. In individual pools, facial zones did not migrate, and finally they were filled with sediments and burried under the association of wave-laminated dolomites. As a result, at the end of the intermediate phase, the quiet-water environments were replaced over the whole region by hydrodynamically active and shallower settings, which dominated the last association.

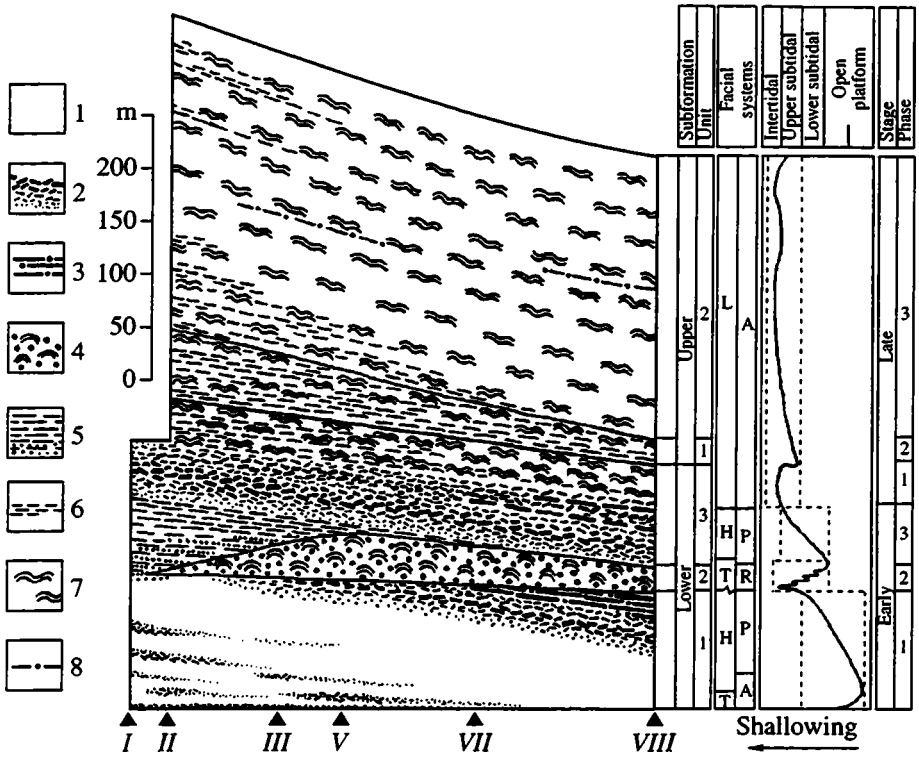

Fig. 4. Facies of the Sukhaya Tunguska Formation and history of the platform development.

1 - 8 – facial associations: 1 – pelitomorphic limestones (dolomites), 2 – clastic limestones (dolomites), 3 – pelitomorphic and clastic limestones, 4 – sandy-stromatolitic association, 5 – horizontally bedded laminites (pelite-siltite and fine-striated types), 6 – dark gray parallel-laminated dolomites, 7 – wave-laminated dolomites, 8 – sandy dolomites.

T, H, L – facial systems: T – transgressive, H – high sea-level, L – low sea-level.

A, P, R – migration regimes of the platform facial zones: A – agraded, P – prograded, R – retrograded. The curve shows sea-level oscillations; stippled line for a range of the oscillations.

The localization of early diagenetic cherts containing abundant silicified microfossils may be related to the enrichment of the described sediments in organic matter. The cherts are mostly confined to boundaries between the dark parallel-laminated dolomites and the light wave-laminated dolomites. This boundary seems to mark the main geochemical barrier of the Sukhaya Tunguska environments, namely the transition from the inner reducing zone of the pools with low pH values and low concentration of dissolved silica, to the hydrochemically contrasting zone, where the association of wave-laminated dolomites accumulated. The presence of noticeable amounts of organic matter might be the cause (or one of the causes) of the relatively long-term unlithified state of the protodolomites of the lower units of the upper subformation. This resulted in abundant syneresis cracks and, at the catastrophic compaction, in diagenetic brecciation.

Thus, the beginning of the intermediate phase coincided with the onset of the short-term transgression during the low sea level stand, which changed neither the earlier facial systems of the platform nor the paleolandscapes. Soon the transgression gave way to the regression. The depositional succession of this phase represents a distinct trend toward shallowing under the agradation regime.

The third, terminal phase of the late stage of the development of the Sukhaya Tunguska platform (the upper unit of the upper subformation) was marked by almost complete domination of the shallowest environments in the peritidal zone, where the association of wave-laminated dolomites with numerous indicators of their shallow water origin accumulated.

A horizon, which occurs approximately in the middle of the unit and includes some thin beds of sandy dolomites, corresponds to the regression peak with the provoked influx of siliciclastic material from the continent. It was said above that this association is composed of carbonate fine-grained sediments accumulating in the lagoons, which were separated by repeatedly emerging sandy shoals.

As we know, the final period of the development of the southern and central parts of the Sukhaya Tunguska platform was distinguished by sediments bearing traces of frequent subaerial exposure (the tepee structures). In the northern sections they are absent, and sediments of deeper settings are represented by parallel-laminated dolomites alternating with the wave-laminated dolo-

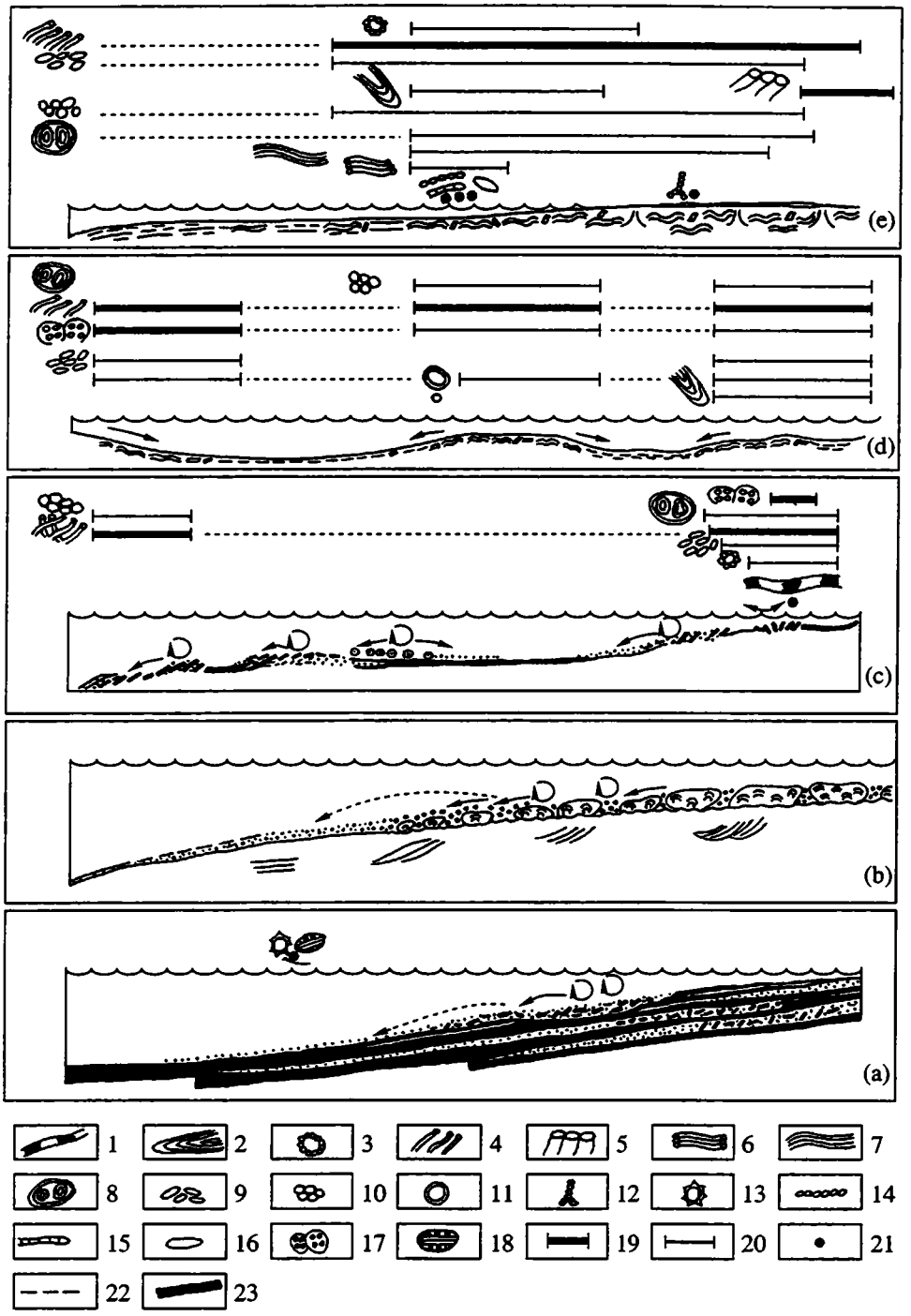

Fig. 5. Depositional environments and distribution of microfossils at the successive phases of the Sukhaya Tunguska platform development.

Early stage: a – the middle of the early phase, b – intermediate phase, the moment of sea level rise (note the lateral change in the lamination type of calcarenites), c – the middle of the late phase. Late stage: d – generalized scheme of the late stage, e – final moment of the platform development (the terminal package of the formation, which contains the tepee structures).

1 - 17 – microfossil taxa: 1 – *Circumvaginalis*, 2 – *Polybessurus*, 3 – *Gyalosphaera*, 4 – *Siphonophycus*, 5 – monogeneric colonies of thick-walled sheaths of *Siphonophycus*, 6 – *Uluksanella*, 7 – *Eomicrocoleus*, 8 – *Gloeodiniopsis* and *Eoaphanocapsa*, 9 – *Eosynechococcus*, 10 – *Myxococcoides* and *Leiosphaeridia*, 11 – *Myxococcoides* cf. *grandis*, 12 – *Eohyella*, 13 – cf. *Trachyhystrichosphaera*, 14 – *Veteronostocale*, 15 – *Calyptothrix*, 16 – *Archaeoellipsoides*, 17 – *Eoentophysalis*; 18 – allochthonous fragments of *Siphonophycus* mats; 19 - 20 – lateral distribution: 19 – main mat-forming forms, 20 – other microfossils; 21 – single occurrences of microfossils; 22 – supposed taxa distribution in nonsilicified facies; 23 – association of pelitomorphic limestones of the lower subformation. For other symbols see Fig. 3.

mites (Figs. 2 and 5). Thus, at the very end of the late Sukhaya Tunguska stage with laterally persistent conditions, the northern part of the basin again became deeper.

It should be noted that facial associations very similar to those of the upper subformation of the Sukhaya Tunguska Formation are widespread in Precambrian basins of different age (e.g., Grotzinger, 1986, 1989; Fairchild *et al.*, 1991) and are commonly treated as peritidal deposits. In our case, this association is dominated by sediments of shallowest waters of the subtidal zone.

THE SUKHAYA TUNGUSKA MICROBIOTA COMPOSITION

The Sukhaya Tunguska microbiota consists mainly of morphologically simple filamentous and coccoidal microfossils, which are mostly the remnants of cyanobacteria. Some of the fossils seem to be eukaryotic unicellular algae. Mendelson and Schopf (1982), who were first to study this microbiota, classified it as "typical Precambrian," i.e., representing the remnants of morphologically simple microorganisms. However, after the discovery of acanthomorphic acritarchs and other microorganisms of complex morphology in the Upper Riphean and Vendian (Neoproterozoic) deposits (for review and bibliography see Knoll *et al.*, 1991; Sergeev, 1992), the above characteristics are suitable for the pre-Riphean and Early and Middle Riphean (Paleo- and Mesoproterozoic) microbiotas only. Moreover, the occurrence of problematic acanthomorphic acritarchs in the Sukhaya Tunguska Formation suggest that the term "typical Precambrian" is inappropriate for this type of biota.

Despite the low diversity of the microbiota morphotypes, there is a long formal list of its representatives. Our materials include 26 species assigned to 19 genera. In addition, Golovenok and Belova (1992, 1993) described or mentioned six extra species of four genera (marked with asterisks in the list below) from the Sukhaya Tunguska microbiota. We neither discovered these microfossils in our material nor consider it possible to use these suggested names. Nevertheless, there is no sufficient information to discredit these taxa. It should be noted that some taxa described by Golovenok and Belova, but missing in our list, seem to be junior synonyms of genera and species accepted herein (e.g., *Eomycetopsis lata* Golovenok et Belova is supposed to be the junior synonym of *Siphonophycus inornatum* Zhang). The detailed substantiation of the taxonomic revision of the Sukhaya Tunguska microfossils will be discussed elsewhere. Here, we only mention that this microbiota includes: *Siphonophycus robustum* (Schopf), *S. inornatum* Zhang, *S. kestron* Schopf, *S.* sp., *Eomicrocoleus* sp., *Circumvaginalis* sp., *Veteronostocale* sp., *Calyptothrix* sp., *Archaeoellipsoides dolichos* (Zhang), *Eosynechococcus moorei* Hofmann, *E. medius* Hofmann, *Sphaerophycus parvum* Schopf, *Eoaphanocapsa oparinii* Nyberg et Schopf, *Tetraphycus giganteus* Zhang*, *Gloeodiniopsis lamellosa* Schopf, *G. magna* Nyberg et Schopf*, *G.* sp.* *Eoentophysalis arcata* Mendelson et Schopf, *Gyalosphaera* cf. *fluitans*, *Polybessurus bipartitus* Fairchild ex Green *et al.*, *Eohyella* cf. *rectoclada*, *Myxococcoides minor* Schopf, *M. inornata* Schopf, *M.* aff. *grandis*, *M.* sp., *Leiosphaeridia* sp., *Globophycus* sp.*, *Uluksanella* sp., cf. *Trachyhystrichosphaera*, *Huroniospora rimosa* Golovenoc et Belova*, and *Glenobotrydion majorinum* Schopf*. In addition, Mendelson and Schopf (1982) also recorded *Oscillatoriopsis media* Mendelson et Schopf which is absent from the materials studied by Golovenok and Belova (1992, 1993) and by us.

The microfossils found are dominated by remnants of hormogonian cyanobacteria and diverse coccoidal forms; other morphotypes occur less frequently or in single specimens.

The empty tubular structures, evidently the sheaths of oscillatorian and nostocalean cyanobacteria, are referred to four species of the genus *Siphonophycus* (Plate, *3*), the most common among filamentous forms. The multicellular trichomes of *Oscillatoriopsis media*, *Calyptothrix* sp. (Plate, *8*), *Veteronostocale* sp., and undeterminable septate filaments are actually the other forms of preservation of the same or similar species of hormogonian cyanobacteria. The empty sheaths of *Circumvaginalis* sp. (Plate, *4*) with dark rings on the surface are likely of the same nature. Similar "banded sheaths" with the characteristic rings on the surface are typical of the modern cyanobacteria *Scytonema* (Monty, 1967, Plate 3, Fig. 3-2) and *Lyngbya* (Kondrat'eva, 1975, Fig. 30.18). The fascines of empty sheaths of *Uluksanella* and indistinct filamentous structures bunched under a common sheath and identified as *Eomicrocoleus* sp. are probably the remnants of polytrichomal filaments similar to the modern *Microcoleus*.

The Sukhaya Tunguska coccoidal microfossils are dominated, as in many other Proterozoic microbiotas, by entophysalidacean cyanobacteria. In the assemblage under consideration, the genus *Eoentophysalis* is represented by one species: *E. arcata* (Plate, *11*, *14*, *16*, and *17*). This species was first described by Mendelson and Schopf as a form of the genus *Eoentophysalis* (Mendelson and Schopf, 1982). Later it was redescribed by Golovenok and Belova (1993, p. 282) as *Eogloeocapsa arcata*, because they noted that these specimens do not have the "sessile forms of polar growth of cells in the colonies typical of entophysalidacean algae." Our ample material exhibits both the sessile forms and distinct polarized growth of cells in the colonies of the microfossils under discussion (Plate, *14* and *17*), features typical of the Entophysalidaceae family but absent in Chroococcaceae (Golubic, 1976; Mendelson and Schopf, 1982).

Among the other coccoidal microfossils known from the Sukhaya Tunguska microbiota, *Gloeodiniop-*

sis lamellosa (Plate, *2* and *10*) should be mentioned first. It forms either independent colonies of loosely spaced spheroids, or close associations with the sheaths of *Siphonophycus*. These microfossils are commonly interpreted as remnants of the chroococcacean *Gloeocapsa*, or *Chroococcus*-like cyanophytes which inhabited the mats of oscillatorian cyanobacteria (Knoll and Golubic, 1979; Sergeev, 1992; and others). More compact colonies of spheroidal or ellipsoidal forms consisting of spheroids similar in size to *Gloediniopsis lamellosa* and identified as *Eoaphanocapsa oparinii*, are the fossil counterparts of the modern cyanobacteria of the genus *Aphanocapsa* or a life cycle stage of *G. lamellosa*.

The abundant, relatively small (less than 10 μm) coccoidal microfossils of this biota are likely to be the remnants of the chroococcacean cyanobacteria, both the benthic and planktonic, comparable to their modern counterparts at the generic and even specific levels. For instance, counterparts of the spherical and tubular colonies of *Gyalosphaera* cf. *fluitans* from the Sukhaya Tunguska rocks (Plate, *13*) should be searched for among the modern planktonic cyanophytes of the genera *Coelosphaerium* and *Gomphosphaeria*, building the tubular colonies with the planar fission of their peripheral cells (Strother *et al.*, 1983). The nature of other larger and smaller coccoidal microfossils is not so clear. Among them, the remarkable and significant components of the microbiota are small ellipsoidal forms referred to the genera *Eosynechococcus* and *Archaeoellipsoides*. Representatives of the first genus (*E. moorei* and *E. medius*) are the remnants of unicellular prokaryotic organisms. They are commonly considered as the fossil counterparts of modern cyanophytes of the genus *Synechococcus* Nägeli comprising genetically different cyanobacteria with simple ellipsoidal forms (Giovannoni *et al.*, 1988). These small cells are difficult to interpret because their simple rodlike form is characteristic of both cyanobacteria and many phototrophic and nonphototrophic bacteria (Knoll *et al.*, 1991). The second genus is represented in our case by one species, the *Archaeoellipsoides dolichos*, and also includes spore remnants of presumably *Anabaena*-like nostocalean cyanobacteria (Sergeev *et al.*, 1995). Although the representatives of the genera *Eosynechococcus* and *Archaeoellipsoides* are similar in appearance, their principal difference is evident from the fact that the *Eosynechococcus* populations show abundant remnants (up to 25% of population) of cells demonstrating various stages of cell fission. There are no signs of cell fission in associations of ellipsoidal microfossils of the genus *Archaeoellipsoides*, which are the remnants of mature spores.

The nature of the abundant representatives of the genus *Myxococcoides*, the unicellular organisms occurring as individual spheroids or their aggregates, is unclear as well. Our material contains the identified representatives of this genus: *M. minor, M. inornata, M.* aff. *grandis* and *M.* sp. varying in diameter from 20 to 65 μm. These spheroids were first described as the remnants of unicellular chroococcacean cyanobacteria (Schopf, 1968) and similarly referred to in most publications on microfossils. But the coccoidal forms of the genus *Myxococcoides* can either be the remnants of green algae (Knoll *et al.*, 1991), or the empty sheaths of prokaryotic colonies (Sergeev, 1992, 1994).

Planktonic forms of the Sukhaya Tunguska microbiota are clearly represented by smooth spherical envelopes, 40 - 60 μm in diameter, referred to the genus *Leiosphaeridia* (Plate, *15*) and problematic remnants of the supposed acanthomorphic acritarchs cf. *Trachyhystrichosphaera*, up to 100 μm in diameter. The representatives of the first taxon are abundant spheroids of simple morphology, which seem to be the remnants of biologically different microorganisms.

Unlike the abundant *Leiosphaeridia*, the remnants of cf. *Trachyhystrichosphaera* are represented in the Sukhaya Tunguska microbiota by three specimens from the lower horizons of the formation (Sample 69). This discovery is significant, as it is ecologically and biostratigraphically informative: the presence of surface spines, when confirmed, would change the accepted Middle Riphean age of the Sukhaya Tunguska formation. It should be emphasized that some features, particularly the size, distinguish the Sukhaya Tunguska cf. *Trachyhystrichosphaera* from the typical populations of the Late Riphean: *T. vidalii, T. stricta* and *T. aimica*.

One of the interesting and widespread specimens of the Sukhaya Tunguska microbiota is the stalked cyanobacterium *Polybessurus bipartitus* (Plate, *5*). It is the usual form of the Upper Riphean and the upper part of the Middle Riphean, but does not occur in older deposits (Green *et al.*, 1987; Knoll *et al.*, 1991; Ser-

Silicified microfossils from the Sukhaya Tunguska Formation.

The microfossil locations are marked with points at the strips of paper attached to the slide margins. *1* – cf. *Trachyhystrichosphaera*, slide 661, Sample 69, point 1; *2, 10* – *Gloeodiniopsis lamellosa*, *2* – slide 518, Sample 38, point 48, *10* – slide 635, Sample 38, point 44; *3* – *Siphonophycus inornatum*, slide 541, Sample 94, point 8; *4* – *Circumvaginalis* sp., slide 617, Sample 85, point 7; *5* – *Polybessurus bipartitus*, slide 531, Sample 38, point 1; *6, 7* – *Eohyella cf. rectoclada*, slide 622, Sample 88, point 10; *8* – *Calyptothrix* sp., slide 518, Sample 38, point 46; *9* – remnants of filamentous microorganisms, slide 518, Sample 38, point 23; *11, 14, 16, 17* – *Eoentophysalis arcata*. *11* – slide 501, Sample 30, point 8, *14* – slide 637, Sample 74, point 42, *16* – slide 637, Sample 74, point 40, *17* – slide 640, Sample 74, point 36; *12* – *Eosynechococcus moorei*, slide 518, Sample 38, point 8; *13* – *Gyalosphaera* cf. *fluitans*, slide 613, Sample 40, point 5; *15* – *Leiosphaeridia* sp., slide 506, Sample 51, point 19.

Stratigraphic and Geographic positions of the samples are shown in Fig. 2.

Single bar scale equals 10 μm, double bar equals 50 μm. All specimens are stored at the Geological Institute of the Russian Academy of Sciences, collection no. 4694.

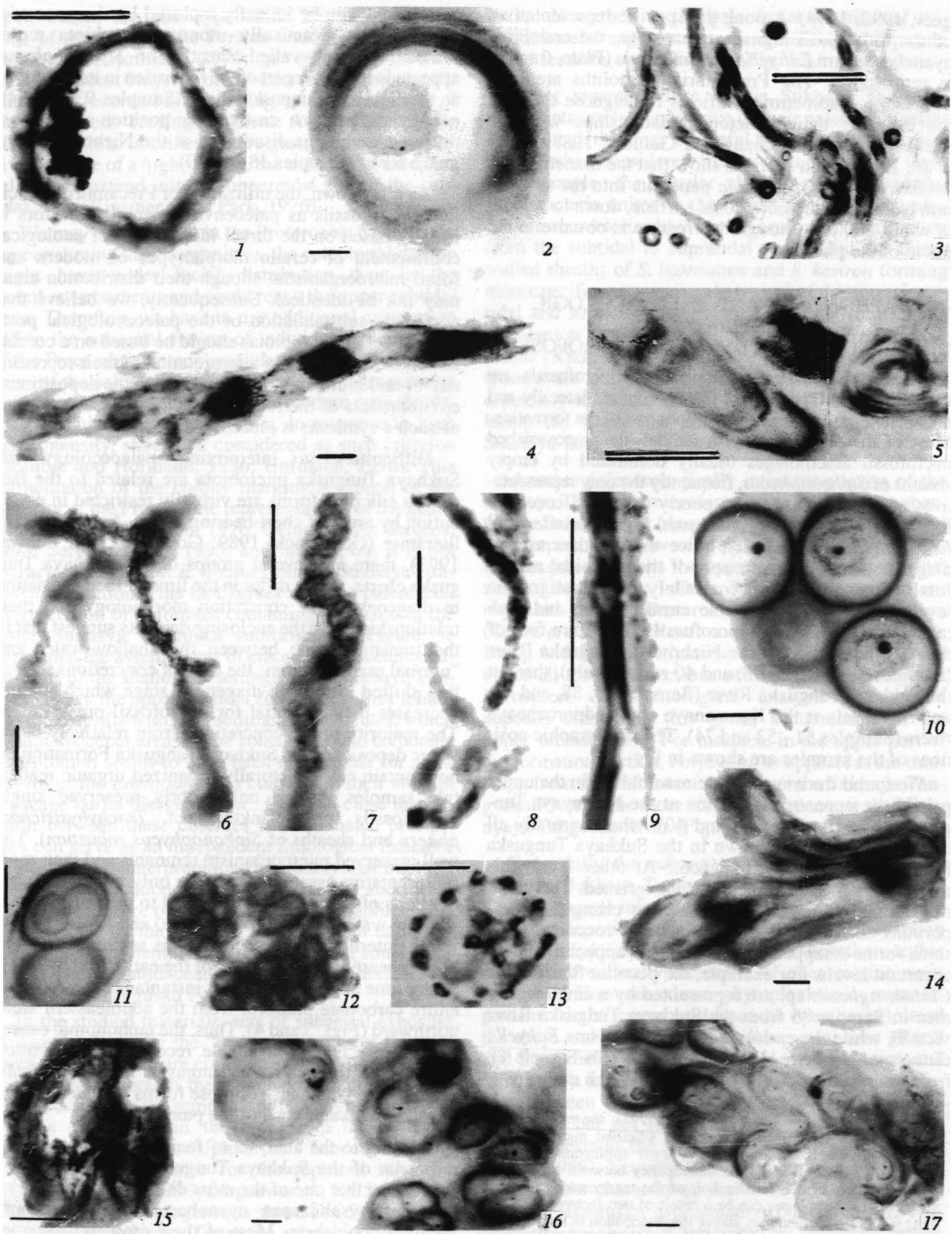

Plate.

geev, 1992, 1994). Among the specific representatives of the Sukhaya Tunguska microbiota, the endolithic cyanobacterium *Eohyella* cf. *rectoclada* (Plate, *6* and *7*) is remarkable. The Precambrian endoliths are rare, because it is sometimes difficult to diagnose them on the basis of their structural relationships with the enclosing deposits (Zhang and Golubic, 1987; Green *et al.*, 1988). Thin sections show that the branching filaments of *E.* cf. *rectoclada* penetrate into the substratum below the microerosional surface, down to a depth of about 200 μm, though this feature is obscure in the photo of the plate.

TAPHONOMIC AND PALEOECOLOGIC INTERPRETATION OF THE SUKHAYA TUNGUSKA MICROFOSSILS

The Sukhaya Tunguska silicified microfossils are unevenly spread throughout the section and laterally and in the bulk, are confined to the upper part of the formation. Most of the studied samples yielded the impoverished microfossil assemblages usually dominated by empty sheaths of *Siphonophycus*, frequently the only representatives of microbiota, and by poorly preserved coccoidal forms of the genera *Gloeodiniopsis, Myxococcoides*, and *Eosynechococcus*. Locally, however, abundant assemblages consist almost entirely of the coccoidal microfossils *Eoentophysalis arcata*. Only a few stratigraphic levels exhibit a considerable concentration and high taxonomic diversity of microfossils. There are four of them in the section at the Nizhnyaya Tunguska River (Samples 28, 32 - 35, 38, and 40 respectively), three at the Sukhaya Tunguska River (Samples 85, 88, and 94) and two levels at the Kamennaya and Nadporozhnaya rivers (Samples 51 - 53 and 74). The stratigraphic positions of the samples are shown in Fig. 2.

We found the most diverse assemblage in the upper part of the upper subformation at the Nizhnyaya Tunguska River (Samples 38 and 40), where virtually all taxa of microfossils known in the Sukhaya Tunguska Formation occur in abundance.[1] At other levels this assemblage is taxonomically impoverished. The variations in taxonomic composition show changeable proportions between the filamentous and coccoidal taxa; some forms disappear and/or rare taxa appear therewith at certain levels. For example, the peculiar filamentous *Circumvaginalis* sp. are represented by a single specimen in Sample 85 from the Sukhaya Tunguska River section, while the endolithic microorganisms *Eohyella* cf. *rectoclada* were distinguished only in Sample 88 from the same section. In addition, the rich microfossil assemblage can be laterally replaced by the poor one. For instance, practically monogeneric biota represented by thick-walled sheaths of *Siphonophycus* appears in the upper part of the formation in its stratotype at the Sukhaya Tunguska River (Samples 93 and 94), occupying the same stratigraphic position as the most diverse assemblage discovered at the Nizhnyaya Tunguska River (Samples 38 and 40).

As it is known, the utilization of Precambrian silicified microfossils as paleoenvironmental indicators is usually based on the direct identication of ecological confinement of certain morphotypes of modern and fossil microorganisms, though their distribution areas may not be identical. Subsequently, we believe that a reliable substantiation of the paleoecological positions of fossil microbiotas should be based on a combination of the actualistic interpretation of their representatives and sedimentological criteria of the depositional environments of the fossiliferous deposits. An attempt of such a synthesis is presented below.

Difficulties in interpreting paleoecology the Sukhaya Tunguska microbiota are related to the fact that its silicified forms are virtually restricted in distribution by areas of chert-bearing facies. As indicated in literature (Golovenok, 1989; Golovenok and Belova, 1993), there are several groups of the Sukhaya Tunguska cherts, which differ in the time of their formation in diagenesis. The concretion morphology and their relationships with the enclosing deposits suggest that in the transition zone between the shallow-water and "normal marine" facies, the time of concretions formation shifted to the late diagenetic stage which sharply decreases their potential for microfossil preservation. The majority of the concretions from relatively deep-water deposits of the Sukhaya Tunguska Formation do not contain any structurally organized organic matter; two samples yielded only poorly preserved single microfossils (phytoplanktonic cf. *Trachyhystrichosphaera* and sheaths of *Siphonophycus robustum*). The well preserved microorganism remnants and their most representative assemblages occur only in certain types of cherts of the formation confined to the sediments of shallow-water (upper subtidal zone) and supershallow-water (intertidal zone) genesis. This sedimentary complex appeared at the very end of the early Sukhaya Tunguska time and spread almost instantaneously over the entire carbonate platform from the southeastern areas northward (Figs. 3 and 4). Thus, the taphonomic causes greatly affected the available records of distribution patterns of the Sukhaya Tunguska microorganisms, favoring the abundance of those forms which inhabited the shallow-water zone of the paleobasin.

Passing to the analysis of facial distribution of the remnants of the Sukhaya Tunguska microfossils, we emphasize that one of the most distinct facial markers, the entophysalidacean cyanobacteria, occurs abundantly among them. Most of their modern analogues inhabit the lower intertidal zone partly isolated from the

[1] According to Golovenok and Belova (1993), the most diverse assemblage of the Sukhaya Tunguska silicified microfossils is confined to the lower part of the upper subformation at the Sukhaya Tunguska River. The discrepancy between their inferrence and ours on the localization of the taxonomically richest microfossil assemblages can be a result of two factors: our sampling is more representative, and/or the distribution of microfossils in the upper subformation is heterogeneous, and subsequently, levels of discovery of rich and poor assemblages are occasional.

open ocean, i.e., the hypersaline basins like Shark Bay of Australia or the Persian Gulf (Golubic, 1976; Golubic and Hofmann, 1976; and others). In the Persian Gulf coast only, the distribution of the entophysalidacean is recorded as depending on the habitat area of the gastropods feeding on them. Accordingly, in the discharge areas of brines, where gastropods cannot survive because of a high salinity, the colonies of entophysalidacean extend into the uppermost part of the subtidal zone (Kinsmann and Park, 1976).

We may suppose that in the Proterozoic basins lacking consuming macroorganisms, the entophysalidacean might have wider facial distribution than in the recent environments and could reach the upper subtidal zone. Therefore, we have to use additional criterion to define the subaerial setting of individual assemblages of the Precambrian entophysalidacean. The dark brown color of the colony margins, probably the relict pigment scytonemine produced by cells of modern cyanobacteria, particularly by *Entophysalis*, in response to high light intensity, should be considered as such criterion (Golubic and Hofmann, 1976; Hofmann, 1976). This pigmentation of the colony margins is typical of the majority of the Proterozoic representatives of the genus *Entophysalis* (Hofmann, 1976; Oehler, 1978; Sergeev, 1993; Sergeev *et al.*, 1995; and others), but it is not characteristic of most *E. arcata* from the Sukhaya Tunguska Formation. This fact agrees with the paleofacial interpretation of dolomites containing *E. arcata* in the upper Sukhaya Tunguska subformation. Figure 5e shows that the assemblages of entophysalidacean occupied one of the shallowest settings of the Sukhaya Tunguska basin: the upper subtidal zone, where they inhabited local uplifts with high sedimentational rates, which separated deeper areas of the zone. The rapid carbonate precipitation seems to have been responsible for polar growth of the *Eoentophysalis* colonies in their attempt to escape burial (Sergeev *et al.*, 1994). A close interrelation between these colonies and laminated precipitates can serve as an independent lithological indicator supporting this interpretation. It is likely that the high rate of sedimentation sometimes led to the short term subaerial exposure of the mentioned local uplifts. This was reflected by the sporadic appearance of dark pigmentation (scytonemine?) in the margins of some colonies of entophysalidacean from the upper horizons of the Sukhaya Tunguska Formation.

In the studied materials, acts of subaerial exposure are clearly shown by the "banded" sheaths of *Circumvaginalis* sp., which are common sheaths with scytonemine bands. Although their Sukhaya Tunguska representatives may be the remnants of hormogonian cyanobacteria different than the type from the Billyakh Group of the Anabar Uplift, the "banded" sheaths themselves are evidence for the repeated subaerial exposure (Sergeev, 1993; Sergeev *et al.*, 1995). Regretfully, among the homogeneous sheaths of *Siphonophycus* from the Sukhaya Tunguska microbiota, there is only a single specimen of the sheath of *Circumvaginalis* sp. Nevertheless, the paleofacial position of this specimen also suggests the repeated subaerial exposure of the fossiliferous sediments (Fig. 5c).

Other representatives of the Sukhaya Tunguska microbiota are less indicative of their paleofacial affinity, although they may be useful for ecological interpretations when considered from a certain point of view. For example, the tubular sheaths of hormogonian cyanobacteria united in the formal genus *Siphonophycus* are characterized by a wide ecological distribution from the subtidal to supratidal zones. But the thick-walled sheaths of *S. inornatum* and *S. kestron* forming monospecific mats were only typical of the upper intertidal and supratidal zones, as it follows from known distribution patterns of the mats in the Precambrian basins (Knoll *et al.*, 1991). The mats of these species sheaths are prevalent in the upper subformation and especially abundant in the Sukhaya Tunguska River basin, the shallowest zone of sedimentation in the Sukhaya Tunguska platform (Fig. 5e).

Another paleoecologically interesting taxon of the Sukhaya Tunguska microbiota is the stalked cyanobacterium *Polybessurus bipartitus*. Its modern undescribed counterpart, which is referred tentatively to the genus *Cyanostylon*, inhabits the upper subtidal and intertidal zone of the Bahama Islands. Similar environments are supposed for the Proterozoic stalked cyanobacteria (Green *et al.*, 1987; Knoll *et al.*, 1991, Sergeev, 1994). Being widespread, *Polybessurus* occurs at several levels of all the main sections of the Sukhaya Tunguska Formation. Sedimentological analysis shows that deposits containing this genus accumulated in the upper subtidal zone. For instance, in the upper part of the formation section, *Polybessurus* appears at the transition from the shallowest deposits at the Sukhaya Tunguska River to the more marine sediments at the Nizhnyaya Tunguska River (Fig. 5e).

Regretfully, the majority of planktonic microfossils from the Sukhaya Tunguska microbiota do not allow for any concrete inferrences on the facial affinity of fossiliferous deposits (Strother *et al.*, 1983). The exception is cf. *Trachyhystrichosphaera*, as the acanthomorphic acritarchs are usually indicative of open marine environments. However, these phytoplanktonic microorganisms can be transported from the open basin toward the shore and buried in the shallow water area (Knoll and Butterfield, 1989; Knoll *et al.*, 1991; Petrov and Veis, 1995). In this case, they show the absence of barriers between intraplatform and open marine parts of the basin, but not for open marine, relatively deep-water genesis of the fossiliferous deposits (Zang and Walter, 1989). Nevertheless, the relatively deep water, open marine character of the lower unit of the lower Sukhaya Tunguska subformation containing cf. *Trachyhystrichosphaera* is supported by our facies reconstructions (Fig. 5a).

Thus, in general, the taxonomic composition of the Sukhaya Tunguska microbiota agrees well with the shallow-water genesis of the fossiliferous deposits and shows the importance of environmental factors in their distribution. Nevertheless, the following patterns of paleoecological distribution of the Sukhaya Tunguska microfossils can be inferred from the predominance of characteristic representatives of benthic assemblages and depositional environments of the fossiliferous strata. The benthic assemblages with dominant entophysalidacean cyanobacteria occupied the marginal parts of the intraplatform pools representing the upper subtidal environments. The specific features of the present *Eoentophysalis* colonies are likely to appear as a response to the increased sedimentational rates. This agress with the estimated high rates of sedimentation in these zones. Other representatives of the Sukhaya Tunguska microbiota colonized a wider range of ecological environments, including those which are below the distribution level of *Eoentophysalis* (species of genera *Eosynechococcus, Archaeoellipsoides, Polybessurus*, etc.). Species of the genus *Siphonophycus* occupied the whole interpretable bathymetric interval, being the dominant or only representative of the microbiota in the shallowest settings. The occurrence of thick pigmented sheaths of *Siphonophycus inornatum* and *S. kestron* in the upper horizons of the formation at the Sukhaya Tunguska River is evidence of the most severe life conditions, including the frequent subaerial exposure. This supports our conclusion that the enclosing deposits accumulated in intertidal and, possibly, supratidal environments.

Regretfully, the materials from even the most fossiliferous upper Sukhaya Tunguska subformation do not provide information on the distribution of microfossils in relatively deep-water settings. The sediments of these environments, typical of internal pool zones, contain only allochthonous fragments of the mats from the adjacent local underwater and emerging uplifts. These sediments are free of any autochthonous biotic elements because of very limited chert formation and, possibly, due to the syngenetic (bacterial?) destruction of the organic remnants in these zones. The lower subformation is more informative with respect to relatively deep-water forms of biota (Fig. 5a). The occurrence of remnants of phytoplanktonic microorganisms (cf. *Trachyhyatrichosphaera*) in its lower parts, which is consistent with the facies reconstructions, supports the interpretation that this part of the subformation was deposited in open marine deep-water settings.

Thus, our conclusions on the paleoecologic confinement of the Sukhaya Tunguska silicified microfossils based on direct sedimentological data coincide with inferences based on the actualistic interpretation of fossil microbiotas and this fact enhances the assurance of the data obtained by each method.

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REFERENCES

Aigner, T., *Storm Depositional Systems,* New York: Springer, 1985.

Assereto, R.L. and Kendall, C.G., Nature, Origin and Classification of Peritidal Tepee Structures and Related Breccias, *Sedimentology,* 1977, vol. 24, no. 2, pp. 153 - 210.

Dionne, J., Vertical Packing of Flat Stones, *Can. J. Earth Sci.*, 1971, vol. 8, no. 12, pp. 1585 - 1591.

Dragunov, V.I., The Turukhansk and Igarka Regions, *Stratigrafiya SSSR, T. 2: Verkhnii Dokembrii* (Stratigraphy of the USSR, Vol. 2: Upper Precambrian), Moscow: Geoltekhizdat, 1963, pp. 318 - 331.

Fairchild, I.J., Knoll, A.H., and Swett, K., Coastal Lithofacies and Biofacies Associated with Syndepositional Dolomitization and Silicification: Draken Formation, Upper Riphean, Svalbard, *Precambrian Res.*, 1991, vol. 53, no. 3/4, pp. 165 - 197.

Giovannoni, S.J., Turner, S., Olsen, G.J., Barns, S., Lane, D.J., and Pace, N.R., Evolutionary Relationships among Cyanobacteria and Green Chloroplasts, *J. Bacteriol.*, 1988, vol. 170, pp. 3584 - 3592.

Golovenok, V.K., Precambrian Chert Concretions: Morphology, Genesis, and Significance for Understanding the Ancient Organic World, *Konkretsii Dokembriya* (The Precambrian Concretions), Leningrad: Nauka, 1989, pp. 94 - 102.

Golovenok, V.K. and Belova, M.Yu., Microfossils in Cherts from the Sukhaya Tunguska Formation of the Turukhansk Uplift, *Dokl. Ross. Akad. Nauk*, 1992, vol. 323, no. 1, pp. 114 - 118.

Golovenok, V.K. and Belova, M.Yu., The Microfossils in the Cherts from the Riphean Deposits of the Turukhansk Uplift, *Stratigr. Geol. Correlation*, 1993, vol. 1, no. 3, pp. 279 - 288.

Gorokhov, I.M., Semikhatov, M.A., Baskakov, A.V., *et al.*, Sr Isotopic Composition in Riphean, Vendian, and Lower Cambrian Carbonates from Siberia, *Stratigr. Geol. Correlation*, 1995, vol. 3, no. 1, pp. 1 - 29.

Golubic, S., Organisms That Build Stromatolites, *Stromatolites,* Walter, M.R., Ed., Amsterdam: Elsevier, 1976, pp. 113 - 126.

Golubic, S. and Hofmann, H.J., Comparison of Holocene and Mid-Precambrian Entophysalidaceae (Cyanophyta) in Stromatolitic Algal Mats: Cell Division and Degradation, *J. Paleontol.*, 1976, vol. 50, pp. 1074 - 1082.

Green, J.W., Knoll, A.H., Golubic, S., and Swett, K., Paleobiology of Distinctive Benthic Microfossils from the Upper Proterozoic Limestone-Dolomite "Series," Central East Greenland, *Am. J. Botany,* 1987, vol. 62, pp. 835 - 852.

Green, J.W., Knoll, A.H., and Swett, K., Microfossils from Oolites and Pisolites of the Upper Proterozoic Eleonora Bay Group, Central East Greenland, *J. Paleontol.*, 1988, vol. 62, no. 6, pp. 835 - 852.

Grotzinger, J.P., Cyclicity and Paleoenvironmental Dynamics, Rocknest Platform, Northwest Canada, *Bull. Geol. Soc. Am.*, 1986, vol. 97, no. 10, pp. 1208 - 1231.

Grotzinger, J.P., Facies and Evolution of Precambrian Carbonate Depositional Systems: Emergence of the Modern Platform Archetype, *Controls on Carbonate Platform and Basin Development*, Crevello, P.D. *et al.*, Eds., *Spec. Publ. – Soc. Econ. Paleontol. Mineral.*, 1989, vol. 44, pp. 79 - 106.

Hofmann, H.J., Precambrian Microflora, Belcher Island, Canada: Significance and Systematics, *J. Paleontol.*, 1976, vol. 50, no. 6, pp. 1040 - 1073.

Kinsmann, D.J. and Park, R.K., Algal Belt and Coastal Sabkha Evolution, Trucial Coast, Persian Gulf, *Stromatolites*, Walter, M.R., Ed., Amsterdam: Elsevier, 1976, pp. 421 - 435.

Knoll, A.H., Microorganisms of the Late Precambrian Hunnberg Formation, Nordaustlandet, Svalbard, *J. Paleontol.*, 1984, vol. 58, no. 1, pp. 131 - 162.

Knoll, A.H. and Golubic, S., Anatomy and Taphonomy of a Precambrian Algal Stromatolite, *Precambrian Res.*, 1979, vol. 10, no. 1, pp. 115 - 151.

Knoll, A.H. and Butterfield, N.J., New Window on Proterozoic Life, *Nature*, 1989, vol. 337, no. 6208, pp. 602 - 603.

Knoll, A.H. and Sergeev, V.N., Taphonomic and Evolutionary Changes Across the Mesoproterozoic-Neoproterozoic Transition, *N. Jb. Geol. Palaeontol. Abh.*, 1995, vol. 195, nos. 1 - 3, pp. 289 - 302.

Knoll, A.H., Kaufman, A.J., and Semikhatov, M.A., The Carbon-Isotopic Composition of Proterozoic Carbonates: Riphean Successions from Northwestern Siberia: Anabar Massif, Turukhansk Uplift, *Am. J. Sci.*, 1995, vol. 295, no. 7, pp. 823 - 850.

Knoll, A.H., Swett, K., and Mark, J., Paleobiology of a Neoproterozoic Tidal Flat/Lagoonal Complex: The Draken Conglomerate Formation, Spitsbergen, *J. Paleontol.*, 1991, vol. 65, no. 4, pp. 531 - 570.

Komar, V.A., Stromatolites in the Correlation of the Riphean Reference Sections of Siberia and the Urals, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1990, no. 10, pp. 3 - 15.

Komar, V.A., Semikhatov, M.A., and Serebryakov, S.N., Distribution of Formal Stromatolitic Species in the Riphean of the Uchur-Maiya Region, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1973, no. 7, pp. 124 - 132.

Kondrat'eva, N.V., *Morfogenez i Osnovnye Puti Evolyutsii Gormogonievykh Vodoroslei* (Morphogenesis and Main Ways of Evolution of Hormogonian Algae), Kiev: Naukova Dumka, 1975.

Maslov, V.P., *Stromatolity* (Stromatolites), Moscow: Nauka, 1960.

Mendelson, C.V. and Schopf, J.W., Proterozoic Microfossils from the Sukhaya Tunguska, Shorikha and Yudoma Formations of the Siberian Platform, USSR, *J. Paleontol.*, 1982, vol. 56, no. 1, pp. 42 - 83.

Monty, C.L.V., Distribution and Structure of Recent Stromatolitic Algal Mats, Eastern Andros Island, Bahamas, *Ann. Soc. Geol. Belgique*, 1967, vol. 90, no. 1/3, pp. 55 - 100.

Oehler, D.Z., Microflora of the Middle Proterozoic Balbirini Dolomite (McArthur Group) of Australia, *Alcheringa*, 1978, vol. 2, no. 3/4, pp. 269 - 310.

Ovchinnikova, G.V., Semikhatov, M.A., Belyatskii, B.V., *et al.*, The Pb-Pb Age of the Middle Riphean Carbonate Deposits of Siberia: The Sukhaya Tunguska Formation, Turukhansk Uplift, *Dokl. Ross. Akad. Nauk*, 1994, vol. 339, no. 6, pp. 789 - 793.

Petrov, P.Yu., Depositional Environments of the Lower Formations of the Riphean Sequence, Northern Part of the Turukhansk Uplift, Siberia, *Stratigr. Geol. Korrel.*, 1993a, vol. 1, no. 2, pp. 55 - 66.

Petrov, P.Yu., Structure and Sedimentation Environments of the Riphean Bezymyannyi Formation in the Turukhansk Uplift, Siberia, *Stratigr. Geol. Korrel.*, 1993b, vol. 1, no. 5, pp. 20 - 32.

Petrov, P.Yu. and Veis, A.F., Facial-Ecological Structure of the Derevnya Microbiota: Upper Riphean of the Turukhansk Uplift, Siberia, *Stratigr. Geol. Korrel.*, 1995, vol. 3, no. 5, pp. 13 - 40.

Schopf, J.W., Microflora of the Bitter Springs Formation, Late Precambrian, Central Australia, *J. Paleontol.*, 1968, vol. 42, no. 3, pp. 651 - 688.

Schopf, J.W., Dolnik, T.A., Krylov, I.N., *et al.*, Six New Stromatolitic Microbiotas from the Proterozoic of the Soviet Union, *Precambrian Res.*, 1977, vol. 4, no. 3, pp. 269 - 284.

Semikhatov, M.A., *Rifei i Nizhnii Kembrii Eniseiskogo Kryazha* (The Riphean and Lower Cambrian in the Yenisei Ridge), Moscow: Nauka, 1962.

Semikhatov, M.A., General Problems of Proterozoic Stratigraphy in the USSR, *Soviet Scientific Rev., Sect. G., Geology*, New York: Harwood Acad., 1991, vol. 1, no. 1.

Semikhatov, M.A. and Serebryakov, S.N., *Sibirskii Gipostratotip Rifeya* (Siberian Hyperstratotype of the Riphean), Moscow: Nauka, 1983.

Serebryakov, S.N., *Osobennosti Formirovaniya i Razmeshcheniya Rifeiskikh Stromatolitov Sibiri* (Peculiarities of Formation and Distribution of Riphean Stromatolites in Siberia), Moscow: Nauka, 1975.

Sergeev, V.N., *Okremnennye Mikrofossilii Dokembriya i Kembriya Urala i Srednei Azii* (Silicified Precambrian and Cambrian Microfossils from the Urals and Central Asia), Moscow: Nauka, 1992.

Sergeev, V.N., Silicified Riphean Microfossils of the Anabar Uplift, *Stratigr. Geol. Korrel.*, 1993, vol. 1, no. 3, pp. 35 - 50.

Sergeev, V.N., Microfossils in Cherts from the Middle Riphean (Mesoproterozoic) Avzyan Formation, Southern Ural Mountains, Russian Federation, *Precambrian Res.*, 1994, vol. 65, no. 1, pp. 231 - 254.

Sergeev, V.N., Knoll, A.H., Kolosova, S.P., and Kolosov, P.N., Microfossils in Cherts from the Mesoproterozoic (Middle Riphean) Debengda Formation, the Olenek Uplift, Northeastern Siberia, *Stratigr. Geol. Korrel.*, 1994, vol. 2, no. 1, pp. 23 - 38.

Sergeev, V.N., Knoll, A.H., and Grotzinger, J.P., Paleobiology of the Mesoproterozoic Billiakh Group, Anabar Uplift, Northeastern Siberia, *J. Paleontol.*, 1995, vol. 69, Mem. 39.

Strother, P.K., Knoll, A.H., and Barghoorn, E.S., Microorganisms from the Late Precambrian Narssarssuk Formation, Northwestern Greenland, *Palaeontology*, 1983, vol. 26, no. 1, pp. 1 - 32.

Veis, A.F. and Semikhatov, M.A., Lower Riphean Omakhta Assemblage of Microfossils from Eastern Siberia: Composition and Formation Conditions, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1989, no. 5, pp. 36 - 55.

Veis, A.F. and Vorob'eva, N.G., Microbiotas of the Kerpyl' Group in the Siberian Hypostratotype of the Riphean, *Stratigr. Geol. Korrel.*, 1993, vol. 1, no. 1, pp. 41 - 58.

Veis, A.F. and Petrov, P.Yu., The Main Peculiarities of the Environmental Distribution of Microfossils in the Riphean Basins of Siberia, *Stratigr. Geol. Korrel.*, 1994, vol. 2, no. 5, pp. 397 - 425.

Vidal, G. and Nystuen, J.P., Micropaleontology, Depositional Environments and Biostratigraphy of the Upper Proterozoic Hedmark Group, Southern Norway, *Am. J. Sci.*, 1990, vol. 290-A, pp. 170 - 211.

Zang, W. and Walter, M.R., Latest Proterozoic Plankton from the Amadeus Basin in Central Australia, *Nature*, 1989, vol. 337, no. 6208, pp. 642 - 645.

Zhang, Y. and Golubic, S., Endolithic Microfossils (Cyanophyta) from Early Proterozoic Stromatolites, Hebei Province, China, *Acta Micropalaeontol. Sinica*, 1987, vol. 4, no. 1, pp. 3 - 15.

Stratigraphy and Geological Correlation, Vol. 3, No. 6, 1995, pp. 621 - 628. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 3, No. 6, 1995, pp. 100 - 107.
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International Symposium on Stratigraphy, Events, and Mineral Resources of the Permian (Guiyang, China, 1994) and the Principal Problems of Permian Stratigraphy (International Symposium on Permian Stratigraphy)

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Abstract – The present publication considers a range of stratigraphic, paleontological, and paleogeographic problems, which were discussed at the International Symposium on Stratigraphy, Events, and Mineral Resources of the Permian (Guiyang, China, 1994). Attention was focused on the problem of lower and upper boundaries of the Permian, as well as on the critical evaluation of the new stratigraphic scale of the Permian, which was presented at the International Subcommission of the Permian Stratigraphy (ISPS) meeting during the symposium. The subsequently published modified version of this scale was also considered. Brief summaries of communications on paleo- and biogeography of the Permian are given.

Key words: *Permian, stratigraphy, paleogeography, paleobiogeography*

The International Symposium on Permian Stratigraphy, Environments and Resources was held in Guiyang (Guizhou province, China), August 28 - 31, 1994. The symposium attracted 80 delegates from 12 countries. A presymposium excursion provided a chance to observe the boundary sections of the marine Permian and Triassic deposits (Meishan, Shangsi, and Hushan). The postsymposium excursions were oriented to study marine Permian sequences in the Guizhou and Guangxi provinces and continental Permian and Triassic sections in the Xinjiang province.

Four sections operated during the symposium: (1) Subdivisions and correlation of the Permian; (2) Flora and fauna of the Permian; (3) Late Permian extinction and Early Triassic regeneration; (4) Permian sedimentology and paleogeography. Among the 73 reports and poster presentations at the symposium, more than half were presented by Chinese specialists. The bulk of the presentations addressed stratigraphy and received special attention because of the discussion on urgent problems of the detailed subdivision and correlation of the Permian deposits. The discussion took place at the meeting of the International Subcommission on Permian Stratigraphy (ISPS), which was held at the beginning of the symposium. Three main problems were discussed: (1) Lower boundary of the Permian; (2) New scheme of the Permian subdivision into series and stages; (3) Upper boundary of the Permian. We will follow these topics in our review of the results presented at the symposium and at the meeting of the Permian Subcommission.

The lower boundary of the Permian. The problem of the lower boundary of the Permian was for many years the central focus of the activity of the Permain Commission of the Interdepartmental Stratigraphic Committee of Russia. After long and comprehensive discussion, the boundary was drawn at the base of the goniatite zone *Svetlanoceras-Juresanites* and the fusulinacean zone *Sphaeroschwagerina vulgaris-S.fusiformis*. This position of the boundary was actively discussed during the Congress on "Permian of the Globe" (city of Perm', 1991) and was adopted by most participants. A Russian–American working group was organized at that time to carry on additional research of the selected boundary stratotype in the Aidaralash section in the Aktyubinsk region of Kazakhstan. The materials accumulated by the group (mainly data on sedimentology and conodont distribution), contributed much to enhancing previous works and enabled a more detailed substantiation of the boundary, including its correlation with the conodont scale.

During the meeting of the International Subcommission on Permian Stratigraphy (ISPS) V.I. Davydov (Russia) presented a report on the behalf of the

Table 1. Chronostratigraphic scale of the Permian (the version discussed at the ISPS)

System	Series	Stage
Permian	Lopingian	Changhsingian
		Dzulfian (Wuchiapingian)
	Guadalupean	Capitanian
		Wordian
		Roadian
	Chihsian (Cathedralian)	Kubergandian
		Bolorian
	Uralian	Artinskian
		Sakmarian
		Asselian

working group. He reported the results of the group's activity and proposed to adopt the Russian model of the Carboniferous-Permian boundary as the global standard. Selection of the Aidaralash section of the southern Urals as the stratotype of the Carboniferous-Permian boundary precisely corresponding to the base of the bed 19/17 was also favored by American experts K. Spinosa, V. Snyder, and R. Belasky (*International ...*, 1994). This suggestion was supported by all participants. According to the current procedure, ISPS members will be questioned by correspondence and in the case of a positive result of the voting (not less than 60% of "pro" votes), all the materials on the problem under discussion will be sent to the International Committee on Stratigraphy (ICS). It is anticipated that during the XXX International Geological Congress in 1996 (China) this boundary will be approved as a global standard.

The boundary between the Carboniferous and Permian was discussed in several presentations. The above variant was supported by American paleontologists Boardman, Nestell, and Wardlaw (*International ...*, 1994) who established this boundary on the basis of conodonts in sections of Kansas, and thus demonstrated the possibility of recognizing the South Uralian variant of the boundary within the limits of a midcontinent. This resulted in the approval of the position by the entire American delegation.

Chinese scientists demonstrated a somewhat different approach in defining the Carboniferous-Permian boundary (Chen Gen-bao *et al.*; Sun Qiao-li; Xia Guoying *et al.*: *International ...*, 1994). These specialists suggested that the appearance of subsphaerical fusulinids (formally called "*Pseudoschwagerina*") be the criterion of the boundary position. In most Chinese sections, this boundary corresponds approximately to the base of the *Daixina bosbytauensis-D. robusta* Zone, which is lower than the aforementioned level. The similar view was discussed in a report by Z.P. Mikhailova and V.A. Chermnykh (Institute of Geology, Syktyvkar), who also determined the position of the Permian-Carboniferous boundary at the base of the *Daixina robusta* Subzone within the *Sphaeroschwagerina vulgaris-S. fusiformis* Zone. However, it should be reminded that this variant was previously considered by the Commission on the Permian System and rejected after lengthy discussions and special investigations.

The scale of the Permian. During the meeting of the ISPS, Jin Yugan, Sheng Jinzhang (China), B. Glenister (USA), and G.V. Kotlyar (Russia) presented for consideration a new chronostratigraphic scale of the Permian. Unlike the traditional Uralian scale, this one is based completely on marine sequences. The scale and its grounds had been published in a special collection of papers by the beginning of the symposium (Jin Yugan *et al.*, 1994a). The scale is given in Table 1.

The authors of the scheme suggested that it be used as a basis for the development of a general chronostratigraphic scale. Their most important arguments are as follows: (1) the scale is fully based on sequences of marine deposits; (2) it has a good paleontological substantiation because all the boundaries are calibrated using the conodont scale; (3) the scheme is a sort of compromise and should satisfy most interested students.

During the subsequent discussion, the scale did not find active support. A. Baud (Swiss), J.M. Dickins (Australia), and E.Ya. Leven (Russia) opposed the proposed scale. The voting showed 9 "pros," including the authors, the Chair of the Bureau of ICS J. Remane, and ICS General Secretary C.H. Gohrbandt, 4 votes against, and 15 abstaintions.

Though the necessity of the marine scale itself is beyond question, the negative reaction to the proposed version resulted from its unfinished and controversial character. The main objections against the discussed scale can be summarized in several points:

(1) In general, the scale is formal and does not reflect the natural events of the Permian history, especially by subdividing the system into series. Here we have to add some remarks concerning the history of this question. During the Congress in Perm' in 1991, the American delegation proposed the three-unit subdivision of the Permian (Glenister *et al.*, 1992), with the middle series termed Guadelupian and having the stratotype in Texas. E.Ya. Leven (1992) proposed a four-unit scale as an alternative, in which the series boundaries corresponded to major biota reorganization stages, associated with global regressions followed by transgressions. These regressions are known to be typical of the initial horizons of the Yahtashian (Artinskian), Kubergandian, and Dzhulfian stages. The series of this scheme were united into two superseries, with the boundary in between coinciding with the universally adopted boundary of the two-unit scale which provides

that the new scale would be successive relative to the traditional scale.

The scale proposed for consideration in Guiyang also demonstrates the subdivision of the Permian into four series. However, the boundaries between them do not mark any past stratigraphic event. For example, the boundary between the Uralian and Chihsian series, which is drawn between the Artinskian and Kungurian (Yahtashian and Bolorian of the Tethyan scale) stages, does not coincide with any important biotic or abiotic event. On the contrary, the major biotic changes at the boundary between the Bolorian and Kubergandian were proposed indicating only the stage boundary.

(2) The scale is completely based on conodonts and often conflicts with data on other groups of organisms. This is especially evident from the position of the Roadian Stage above the Kubergandian Stage. The point is that there are well known finds of ammonoids confined to the base of the latter stage, and their forms are correlative with the Roadian forms (Leonova and Dmitriev, 1989). The authors posed the Roadian Stage above the Kubergandian using conodonts (*Mesogondolella nankingensis*) from the lower third of the Murgabian Stage of the Tethyan scale, where the latter overlies the Kubergandian Stage. In American sections, these forms are identified as *Mesogondolella serrata* and are also recognized in the Road Formation. These forms of conodonts occur in sections southern China as well. One such section, the Luodian, was revealed during excursions. Direct examination of the section suggests the reworking of both the fusulinids and conodonts at the Kubergandian level. After a study of the specimens of these fossils, this inference was shared by conodont experts H. Kozur and B. Wardlaw. It is clear that the present problems may be solved only by additional studies. Such studies are highly desirable, as the results are important not only for clarifying the relationships between these two stages, but also for positioning the series boundaries, and eventually, identifying the number of series. For instance, if the Kubergandian and Roadian stages are synchronous, then the volume of the Chihsian Series will drop to the single Bolorian (Kungurian) Stage. In turn, it will question the necessity of this series itself.

The data on the upper limit of the Guadalupian Series is also conflicting. Three variants of its relationships with the Lopinian Series are discussed soley on the basis of conodonts. One of them even includes the recognition of a new stage between the Capitanian and Dzhulfian (Wuchiapingian) (Kozur, 1994; Mei Shilong *et al.*, 1994). Data on other groups of marine organisms are equally controversial. For instance, in many sections the Capitanian (Midian) ammonoids of the *Timorites* Zone are confined to beds corresponding to the Wuchiapingian on the basis of conodonts (Zhou Zuren, 1994). The same is true for the Kalabah Beds of the Salt Range. These deposits contain numerous brachiopods, which are obviously older than the Dzhulfian forms. At the same time, the conodonts from the Kalabah Formation are determined as Dzhulfian in age (Jin Yugan *et al.*, 1993).

The problem of the fusulinacean zone *Lepidolina kumaensis* was another subject of controversy. G.V. Kotlyar (of the All-Russia Geol. Inst.) presented evidence indicating its pre-Wuchiapingian (Midian) age. The most important evidence is the discovery of *L. kumaensis* in the pre-Wuchiapingian Maokou Formation. However, this argument was questioned by E.Ya. Leven. In his opinion, the forms described by Rui Lin (1983) as *L. kumaensis* are more primitive and should be attributed to a different species. From this viewpoint, the *L. kumaensis* zone could be correlated with the lower part of the Wuchiapingian Stage.

(3) The proposed scale is "*combinatory*." The lower series is based on the Uralian sequence; the Chihsian and Lopingian are adopted from the Tethys region, and the Guadalupian is member of the North American scales. The idea to cut a part of the Tethyan scale and substitute it with the American Guadalupian series seems unreasonable to most specialists, because it leads to numerous problems when tracing the American stages in Euroasian basins. In addition, the neighboring position of Paleo-Tethys and basins of the Boreal and Nothal climatic zones is favorable for detailed correlations of all Eurasian sections. This latter point was emphasized by T.A. Grunt (Paleontol. Inst. Ross. Acad. Sci.). In her opinion, the North American sections of the tropical climatic zone have a high degree of biogeographic isolation due to their marginal geographic position. The biota in the respective basins was highly endemic, and the main groups of marine invertebrates had peculiar rates of evolution. This confirms the extremely low correlative significance of the North American sections, despite their completeness and rich fossil content.

All of these comments concern only the principal disadvantages of the scale, which is imperfect in other aspects as well. Most participants of the symposium shared the opinion that the scale needs to be improved. It is not appropriate to hasten this situation, and before consideration of the scale by the ISPS, the correlation charts should be approved. Only after this would it be possible to discuss the number of series and stages and to name them on the basis of the priority principle.

The correctness of this thesis is illustrated by the new version of the scale, which was published two months after the end of the symposium (Jin Yugan *et al.*, 1994b). The scale was substantially modified in the following respects (Table 2):

(1) The Permian is subdivided into two superseries and four series in accordance with the proposals of E.Ya. Leven.

(2) The Chihsian Series is renamed as Leonardian; The Bolorian and Kubergandian series are renamed as Hessian and Cathedralian.

Table 2. Chronostratigraphic scale of the Permian (revised version)

System, Series, Stage			Ammonite zones	Conodont zones	Fusulinacean zones	
Triassic			*Ophiceras*	*Hindeodus parvus*		
Upper Permian	Lopingian		*Otoceras*			
		Changhsingian	*Rotodiscoceras* *Pseudotirolites-Pleuronodoceras*	*Clarkina changxingensis*	*Palaeofusulina sinensis*	
			Pseudostephanites-Tapachanites			
			Paratirolites-Shevyrevites	*C. subcarinata*	*P. minima*	
			Iranites-Phisonites			
		Wuchiapingian	*Sanyangites*	*C. orientalis*		
			Araxoceras-Konglingites	*C. transcaucasica*	*Gallowayinella meitiensis*	
			Anderssonoceras-Prototoceras	*C. leveni* *C. assymmetrica* *C. dukouensis*	*Nanlingella simplex-Codonofusiella kwangsiana*	
			Roadoceras-Doulingoceras	*C. postbitteri*		
	Guadalupian	Capitanian	*Timorites*	*M. xuanhanensis* *M. prexuanhanensis* *M. altudaensis*	*Paraboultonia*	*Yabeina-Lepidolina*
					Reichelina	
					Paradoxiella	
				M. shannoni	*Polydiexodina*	
				M. postserrata	*Codonofusiella*	*N. margaritae*
		Wordian	*Waagenoceras*	*M. aserrata*	*P. antimonioensis*	*N. deprati*
					P. sellardsi	*N. simplex*
		Roadian	*Damarezites*	*M. nankingensis*	*P. rothi*	*C. cutalensis*
			Paraceltites elegans		*P. boesei*	*M. ovalis*
Lower Permian	Leonardian	Cathedralian	*Stacheoceras discoidale*	*N. sulcoplicatus*	*P. fontaini*	*M. parvicostata*
			Sosiocrimites	*M. zsuzsannae*	*P. durhami*	*M. claudiae*
			Perrinites ex gr. *hilli*		*P. setum*	
		Hessian	*Pseudovidrioceras dunbari*	*N. prayi*	*P. leonardensis*	
			P. compressus	*M. idahoensis*	*Skinnerella* spp.	*B. dyhrenfurthi*
			Propinacoceras busterense	*N. pnevi/N. exsculptus/ M. gujioensis*	*Schwagerina* spp.	
	Preuralian	Artinskian	*Uraloceras fedorovi*	*N. pequopensis*	*P. sollidissima*	*Ch. vulgaris*
			Aktubinskia notabilis	*S. whitei-M. bisselli*	*Ps. juresanensis*	*Pamirina*
			Artinskia artiensis		*Ps. pedissequa*	*Ch. solita*
		Sakmarian	*Sakmarites inflatus*	*S. primus-M. visibilis* *S. merrilli*	*Ps. uralensis*	*R. schellwieni-Paraschw. mira*
					Ps. verneuili	
			Svetlanoceras strigosum	*M. longifoliosa*	*Ps. moelleri*	
		Asseliaan		*S. postfusus*	*Sphaeroschw. sphaerica-Ps. firma*	
			S. serpentinum	*S. fusus*		
			S. primore	*S. constrictus*	*Sphaeroschw. moelleri-Ps. firma*	
				S. barskovi	*Sphaeroschw. vulgaris-S. fusiformis*	

(3) The Hessian, Cathedralian, and Roadian stages are correlated with the fusulinid zones constituting the Bolorian (*B. dyhrenfurthi-M. parvicostata* Zone), and Kubergandian (*M. ovalis-C. cutalensis* Zone) stages of the Tethyan scale.

Thus, it is clear that the changes are considerable. At the same time, the authors obviously used the data base of the first version of the scale, but interpreted it in a different manner taking into account the criticism expressed at the symposium. The simplicity of these changes shows that the scale is insufficiently controlled by the factual data, which is inadequate for unambiguous conclusions. Also noteworthy is that the priority principle in the introduction of the North American names of stages is overlooked. According to the correlation with the fusulinid zones presented in the scale, the Leonardian Series is the complete analog of the Bolorian, while the Roadian, Wordian, and Capitanian stages completely coincide with the Kubergandian, Murgabian, and Midian stages of the Tethyan scale respectively (Leven, 1980). If so, the scale should use the Tethyan names, which have an apparent priority over the North American terminology.

Reports of the symposium did not touch upon the problems of the Permian scale itself. Only B. Glenister (*International* ..., 1994) reported on the general concept of the scale, which is based on the valid conodont boundaries. His proposals differ from the above version only with respect to the Chihsian Series, which he suggested to be based on American sections under the name Cathedralian Series.

In view of the problems under discussion, the most interesting were the reports considering new paleontological and biostratigraphic data. The reports of Chinese specialists, who worked very intensively over the last several years, were the most informative. First of all, the remarkable report on the boundary between the Maokou and Wuchiaping formations was given by Jin Yougan and others (1994). Also worth mentioning are the reports of Mei Shilong and Wang Zhihao devoted to conodonts, and the reports of Sun Quiao-li and Zhu Zili and Zhang Linxin on fusulinids (*International* ..., 1994). Interesting information was presented in several other reports: V.I. Davydov (Russia) described the fusulinid zonation of the Murgabian and Midian; H. Kozur (Hungary) reported on stratigraphy of the Loping Formation; M. Echiro (Japan) presented characteristics of ammonoids from the Kitakami Mts.; B. Wardlaw (USA) summarized data on conodonts of the Cathedral Formation (*International* ..., 1994). In sum, there has been considerable progress in conodont studies, and in many cases they provide grounds to discuss direct correlations between the Tethyan and North American sections. However, the conodont data poorly corresponds to the data on fusilinids, though the latter are the key fossils for the Permian scale of the Tethys. This is the main obstacle in creating the universal scale, as it became clear from discussion at the ISPG meeting.

The upper boundary of the Permian. This problem was the focus of the activity of the special "Permian-Triassic boundary Workgroup" (PTBWG). This group was organized by the Permian and Triassic Subcommissions of the International Stratigraphic Committee. The group has been headed by the prominent Chinese paleontologist Yin Hongfu since 1992. It is well known that the Permian-Triassic boundary is located at the base of the Himalayan *Otoceras woodwardi* Beds. In sections of the eastern basins (Arctic Canada, Eastern Greenland, Spitsbergen, Northeastern Siberia) and along the northern shelf of Gondwana (Himalayas, southern Tibet) the *Otoceras* Beds unconformably overlie the Permian strata of different ages. A considerable part of the Upper Permian may frequently be absent. According to the International Stratigraphic Code, sequences with significant stratigraphic hiatuses are unacceptable for the global stratotype boundary point (GSSP). Therefore, Yin Hongfu suggested the Meishan section of the southern China (Changhsing) to be the stratotype of the boundary between the Permian and Triassic. This section includes a continuous sequence of Changhsingian-Griesbachian Beds. The following units are recognized in the section in ascending order: (1) the *Paratirolites* Zone; (2) the *Pseudotirolites-Pleuronodoceras* Zone; (3) boundary clay bed with Changhsingian conodonts; (4) the lower *Otoceras woodwardi* Zone or the *Otoceras latilobatum* Zone; (5) the *Hindeodus parvus* Zone; (6) the *Isacicella isarica-Claraia-Ophiceras* acme zone. Analogues of these units are easily recognizable in many Tethyan sequences. Yin Hongfu suggested to place the global stratotype boundary point at the base of the conodont *Hindeodus parvus* Zone. He considers the base of the *Otoceras* Zone only as an auxiliary reference level.

During the discussion of this problem at the PTBWG meeting held on August 29, the overwhelming majority of participants supported the viewpoint of Yin Hongfu concerning the selection of the Meishan section as the boundary stratotype. Only A. Baud from Switzerland favored the Guryul Ravin section in Kashmir. However, opinions differed on the precise position of the boundary level. Some researches supported the variant proposed by Yin Hongfu. Among others, H. Kozur once more drew attention to his view of the age synchronism of the *Otoceras* Beds and the upper part of the Changhsingian deposits (from the *Tapashanites* Zone to the *Rotodiscoceras/Pleuronodoceras* Zone included). This viewpoint is based on the presence of Changhsingian conodonts in the *Otoceras* Beds. However, Canadian specialist Orchard recently (1994) questioned Kozur's conclusions. According to his studies, in the Selong section of Southern Tibet *H. parvus* appears at the base of the *Otoceras* Beds in the *O. latilobatum* Zone. This zone is equivalent to the lower *Otoceras concavum* Zone of the Triassic sequence in Arctic Canada. After studying the conodonts from the Permian-

Triassic boundary deposits of numerous Tethyan sections, Orchard concluded that the idea on the synchronous age of the *Otoceras* Beds and the upper parts of the Changhsingian (Dorashamian) is doubtful. At the same time, a Canadian group (Wang, Geldsetzer, and Krouse, 1994) demonstrated slides on the Selong section with distinct unconformity at the base of *O. latilobatum* Beds where *H. parvus* was discovered. In discussion, there were opinions about possible conodont redeposition here. However, V.R. Lozovsky (Russia) rationally argued that the redeposition was not the case with *H. parvus*, because this form does not occur below the *Otoceras* Beds.

An opinion different from that of the working group, was presented by J.M. Dickins (Australia), V.R. Lozovsky, and some others. In their view, the boundary should be traditionally placed at the base of the *Otoceras* Beds. V.R. Lozovsky stressed that the boundary position at the base of the *H. parvus* Beds creates insuperable problems for tracing it in marine sections of boreal basins and in continental facies. An alternative idea is to place the boundary at the base of the "Mixed bed 1" (black clay). This thin (6 cm) layer of pyrite-bearing clay is distinct from the underlying Permian deposits. Though the bed still contains the Permian brachiopods, conodonts, and ammonoids *Pseudogastriceras* sp., the first occurrence of Triassic ammonoids is recorded here. In addition to *Otoceras*? sp., *Hypophiceras* cf. *martini* Trumpy and *H. changhsingensis* also occur here. Shevyrev (1990) attributed the last two species to the genus *Metophiceras*, which appeared together with *Otoceras* in many sequences of boreal and Tethyan basins. These forms, which externally resemble the Permian Xenodiscidae, are sometimes erroneously considered to be within the same family. However, they sharply differ from the Permian species in their patterns of external suture, which is the basis for the ontogeny of all Triassic ammonoids.

In his concluding remarks Yin Hongfu focussed on the problem of correspondence between the ammonite and conodont scales. In fact, the positioning of the Permian-Triassic boundary is directly dependent upon the decision of which scale is more preferable. It is planned to distribute a questionare on this issue in the near future.

A number of reports presented new data on boundary layers of the Permian in various regions of the world, such as British Columbia and Canada (K. Wang, H. Geldsetzer, and H. Krouse), Iran (F. Golshani and H. Partoazar), North Vietnam (Dang Tran Huyen), Selong (H. Geldsetzer, and the joint report of Sen Shu-zhong and Jin Yu-gan), and various regions of Southern China (Lai Xulong *et al.*, Zhu Xiangshui *et al.*, Yin Hongfu; see *International* ..., 1994).

An interesting report of G. Wood and G. Mangerud (*International* ..., 1994) was devoted to the so-called "micofloral event" recorded in the Permian-Triassic boundary deposits in various regions of the world (Greenland, Arctic Canada, Spitsbergen, South Alps, Russia, China, Australia, Israel, Tunisia). Palynological assemblages of this age show a high content of fungi-like filiform fossils, such as *Tymphanicysta stoschiana* and others. Negative anomalies of $\delta^{13}C$ and $\delta^{18}O$ are also recorded at this level. The authors interpret this phenomenon as a consequence of the Late Permian transgression, which caused the drying of considerable shelf areas. The subsequent oxidation of organic carbon produced an increase of the CO_2 and decrease of the O_2 contents in the ocean–atmosphere system, which favored the mass development of fungi.

Problems of Permian paleogeography and biogeography. All reports concerning the distribution of certain groups of marine organisms or land plants used the plate-tectonic reconstructions. Most authors applied the schemes of Scotese and McKerrow (1990) with some modifications. Australian paleontologist G.R. Shi discussed some general aspects of Permian marine biogeography in the western Pacific along with the bipolarity of the Permian marine faunas. In his view, the most important issues are the problems of hierarchy and nomenclature of biogeographic units, and understanding the province evolution and migration of their boundaries. A number of reports analyzed the horology of certain groups of marine invertebrates. Among these are the reports of M. Echiro (Japan) and Ma Junwen (China) on ammonoids, E.H. Gilmor and L.M. Neyens (USA) on bryozoans, and T.A. Grunt (Russia) on brachiopods (*International* ..., 1994). Several reports were dedicated to the sedimentology and paleogeography of peri-Gondwanan regions. Thus, Chinese paleontologist Liu Guanghia considered the details of the Permian sedimentation in the territory of Tibet and the Himalayas. The author emphasized that during the Early and initial Late Permian these areas existed as microcontinents with a distinct character of sedimentation, and evolution of faunal and floral assemblages, which were typical of the Gondwana supercontinent and its shelf. Swiss geologist A. Baud considered the paleogeography of North Indostan (including the Higher and Lower Himalayas, Chamba, Nepal, and Kashmir) during the Late Permian formation of an active rift zone in this area and the initial opening of the Neotethys basin. Australian scientist I. Metcalf addressed the paleogeography of eastern and southeastern Asia, interpreting it as the migration history of terranes which were constitutients of Gondwana during the Late Carboniferous-Early Permian, and then migrated from the shore line of this continent toward the equator. Subsequently they were amalgamated into the Asian tectonic block. Ni Shangyou (USA) discussed the paleogeography of eastern Asia as a history of complexly interrelated microcontinents. Several reports of Chinese researchers were dedicated to the sedimentological analysis and paleogeography of the Chinese territory as a whole and in parts (Feng Zengzhao *et al.*, Jiang Nayan *et al.*, Liu Fa and Zhang Chua-

nbo, Song Weihai and Song Jiarong, Wang Yue and Jin Yugan, Zhang Zuqi; see *International* ..., 1994).

Without detailing these reports, we will simply note that the concept of Cathaysia representing an undivided continental block, which was popular about ten years ago, is now discredited. Recent studies showed that during the Permian, China and adjacent areas represented an extremely complex system of terrains, island arcs, and marine basins. Their configurations will be clarified by future studies. Also discussed was the paleogeography of the northern Urals, by V.A. Chermnykh (Russia).

The report of Chinese paleobotanists Shen Guanglong and Wang Yongdong was dedicated to the paleofloral provinces of China. For the Early Permian period, they recognized Subangarian, Euramerican (the Tarim Plate), Gondwanan (South Tibet), and Cathaysian phytorealms. The latter is subdivided into northern and southern subrealms, which in turn, consist of a number of provinces. During the Late Permian, the Gondwanan flora disappeared in China, and the Subangarian flora expanded southward, covering the Tarim and Nan Shan mountains. The boundary between the Cathaysian and Angarian realms were considered in the report of Chinese paleontologists Mi Jiarong and Jin Jianhua. It is known from plate-tectonic reconstructions that the distribution areas of these floras were confined to different tectonic blocks separated by an ocean. However, the authors came to the conclusion that the blocks had relatively close positions. They believe that the mentioned areas were separated only by mountain systems of the In Shan and its eastern and western extensions. Chinese paleontologist Yang Weiping maintained that there is significant similarity among the apparently Sakmarian-Artinskian palynological assemblages from the Lower Permian deposits of various parts of Gondwana.

The Permian stratigraphy of continental deposits attracted comparatively less attention at the symposium. V.R. Lozovsky, chair of the working group on the "Permian continental sequence and Permian-Triassic boundary," reported on its activity at the meeting of the ISPS. The group, which was formed at the conference on "Pangea from the Carboniferous to Jurassic" (Calgary, 1993), has the following goals: (1) to encourage study of different groups on continental fauna and flora in various areas of the world; (2) to stimulate the creation of regional biostratigraphic scales, first of all, on tetrapodes, fish, conchostracan, ostracods, insects, flora, miospores, charophytes (specialists on these groups are invited for cooperation); (3) to expeditiously select an international continental stratigraphic standard in addition to the marine standard, which is presently under elaboration; (4) to distinguish the most complete and continuous sequence of the Permian and Triassic deposits in continental series in order to select GSSP.

According to ICS regulations, the question of boundaries between the systems is within the jurisdiction of the "younger" Subcommission, in this case the Triassic Subcommission (SCTS). Accordingly, the boundary problem should be solved in close cooperation with the working group on the "Permian-Triassic Boundary and the continental Triassic scale," (the SCTS group) formed in 1992 headed by American specialist Spenser Lukas. The first meeting of the group is planned for the XIII International Carboniferous Congress to be held in Krakow (Poland) from August 28 to September 2, 1995.

The report of V.R. Lozovsky focused on the problem of P/TGSSP selection. The author shared the opinion of Zheng Wucheng and S. Lukas (1993) that possible choice is the section of the Dalangkou anticline in the Jimsarian basin (Xinjiang), where the boundary is within the red Guodiken Formation. Another viable option is the section in the middle flow of the Vetluga River, the East European Platform. In this section, the boundary beds between the Permian and Triassic contain fauna of land vertebrates, ostracods, conchostracan, freshwater mollusks, and miospore assemblages. Both sections show similar successions of faunal assemblages. However, the East European section has advantages in correlating the lower part of the Vokhma Horizon of the Vetluga Series with the *Otoceras* Beds of East Greenland.

Polish stratigraphers A. Fialkovska and M. Kuleta (*International* ..., 1994) discussed interesting data on the Permian-Triassic boundary beds in southern Poland, where a transition from the regressive cycle of the Permian Zechstein to the transgressive deposits of the Lower Triassic (lower parts of the Buntsandstein) was recorded. G. Johnson (USA) demonstrated the evident correlation potential of the microremains (teeth, scales, ichthyodorulites) of cartilaginous fish from the Wichita Group (Texas).

An interesting joint report was presented by Canadian specialist L. Utting, and N.K. Esaulova and M.N. Grigor'eva from Russia. The report focussed on the problem of correlating the Kazanian deposits in the stratotype area (Tatarstan) and Kolguev Island with the Wordian deposits in the Canadian Arctric Archipelago. It was shown that the palynological assemblages of Kolguev and the Canadian Arctic are more similar to one another than to coeval assemblages from the stratotype area. Provided that all the three localities are in the Angarian floral province, the authors suggested the hot and dry climate of Tatarstan, whereas the Canadian Arctic was presumably situated in a cold and dry climate zone with periodic humidization. At the same time, the southern part of the Barents Sea likely had a rather humid climate.

In conclusion, we would like to express our gratitude to the Organizing Committee of the Symposium and International Science Foundation (ISF) for the opportunity to attend the "International Symposium on Permian Stratigraphy, Environments and Resources."

REFERENCES

Glenister, B.F. *et al.*, The Guadalupian: Proposed International Standard for a Middle Permian Series, *Int. Geol. Rev.*, 1992, vol. 34, no. 9, pp. 657 - 688.

International Symposium on Permian Stratigraphy, Environments and Resources (ISP'94) with International Meeting of Pangea Project GSGP: IGCP 306 and 359. Abstracts, Guiyang, China, 1994.

Jin Yugan, Mei Silong, and Zhou Zili, The Potential Stratigraphic Levels for Guadalupial-Lopingian Boundary, *Permophiles*, 1993, no. 23, pp. 17 - 20.

Jin Yugan, Glenister, B.F., Kotlyar, G.V., and Sheng Jinzhang, An Operational Scheme of Permian Chronostratigraphy, *Palaeoworld 4, Vol. 1: Palaeontol. and Stratigr., Nanjing: Nanjing Univ.*, 1994a, pp. 1 - 13.

Jin Yugan, Sheng Jinzhang, Glenister, B.F., *et al.*, Revised Operational Scheme of Permian Chronostratigraphy, *Permophiles*, 1994b, no. 25, pp. 12 - 15.

Kozur, H., The Permian-Triassic Boundary in Marine and Continental Sediments, *Zbl. Geol. Palaeont.*,1989, part 1, pp. 1245 - 1277.

Kozur, H., Permian Pelagic and Shallow-Water Conodont Zonation, *Permophiles*, 1994, no. 24, pp. 16 - 18.

Leonova, T.B. and Dmitriev, E.Yu., *Rannepermskie Ammonoidei Yugo-Vostochnogo Pamira* (Early Permian Ammonoids from the Southeastern Pamirs), Moscow: Nauka, 1989.

Leven, E.Ya., *Ob'yasnitel'naya Zapiska k Stratigraficheskoi Shkale Permskikh Otlozhenii Oblasti Tetis* (Explanatory Notes to the Stratigraphic Scale of the Permian Deposits in the Tethys Area), Leningrad: Vses. Geol. Inst., 1980.

Leven, E.Ya., The Division of the Permian System at the Series Level, *Permophiles*, 1992, no. 21, pp. 8 - 10.

Leven, E.Ya., The Main Events of the Permian History in the Tethys Area and Fusulinids, *Stratigr. Geol. Correlation*, 1993, vol. 1, no. 1, pp. 51 - 65.

Lozovsky, V.R., Continental Sequence of Permian and P/T Boundary Working Group, *Permophiles*, 1994, no. 25, pp. 9 - 11.

Mei Shilong, Jin Yugan, and Wardlaw, B.R., Succession of Conodont Zones from the Permian "Kuhfeng" Formation, Xuanhan, Sichuan and Its Implication in Global Correlation, *Acta. Paleontol. Sinica*, 1994, vol. 33, no. 1, pp. 1 - 23.

Orchard, M.J., Conodonts from Octoceras Beds: Are They Permian?, *Permophiles*, 1994, no. 24, pp. 49 - 51.

Rui Lin, On the Lepidolina Kumaensis Fusulinacean Fauna, *Bull. Nanjing Inst. Geol. and Paleont., Acad. Sinica*, 1983, vol. 6, no. 6, pp. 249 - 270.

Scotese, C.R. and McKerrow, W.C., Revised World Maps and Introduction. Palaeozoic Palaeogeography and Biogeography, *Geol. Soc. Mem.*, 1990, no. 12, pp. 1 - 21.

Shevyrev, A.A., *Ammonoidei i Chronstratigrafiya Triasa* (Ammonoids and Chronostratigraphy of the Triassic), Moscow: Nauka, 1990.

Yin Hongfu, Reassessment of the Index Fossils at the Paleozoic-Mezozoic Boundary, *Palaeoworld*, 1994, no. 4, pp. 153 - 171.

Zhou Zuren, On the Study of the Boundary Strata between Guadalupian and Lopingian Series, *Permophiles*, 1994, no. 24, pp. 24 - 26.

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Olga Ivanovna Nikiforova (1905 - 1994)

Olga Ivanovna Nikiforova died on December 30, 1994 in St. Petersburg, half a year before her 90th birthday. Nikiforova, an internationally known paleontologist and stratigrapher, prominent specialist on Paleozoic brachiopods and Silurian stratigraphy, and doctor of geology, was the senior researcher at the Karpinskii All-Russian Institute of Geology.

Nikiforova was born into a family of peasants on June 18, 1905, in Varvarinskoe village in the Orenburg province (now Bashkortostan). After completing school in 1924, she entered the Leningrad Geographical Institute, which was later united with the State University; she graduated in 1930. Her scientific career began at the Geological Committee, which was later reorganized into the Central Research Geological Institute, and more recently into the All-Russian Institute of Geology, where she worked for more than 60 years.

Nikiforova's scientific views were formed under the influence of the prominent Russian geologist D.V. Nalivkin, whom she regarded as her teacher. She participated in various expeditions in Central Asia and Ukraine, where she carried out field research and correlated Silurian and Lower Devonian deposits of these regions, and simultaneously prepared a detailed scientific report on paleontological materials practically unstudied and unknown earlier in Russian geological literature. The materials were collected by geological-prospecting groups in northern areas of the country: Novaya Zemlya, Vaigach Island, and Siberia. Nikiforova's active and fruitful work before the Second World War resulted in a number of papers describing the stratigraphy of the Upper Silurian deposits in Kazakhstan, Uzbekistan, Novaya Zemlya, and Podoliya and in a monograph on Upper Silurian brachiopods from Soviet Central Asia (1937), which served as the basis for her candidate of science dissertation (1939).

During World War II, Nikiforova worked in the Urals on a diamond exploring expedition solving practical geological problems. In 1944 she returned to Leningrad to the All-Russian Institute of Geology to resume her research on Paleozoic deposits. She wrote dozens of papers on stratigraphy and paleoecology, which familiarized specialists with the rich Silurian fauna of the Arctic regions and with the Silurian sections of Podoliya, Tadzhikistan, Uzbekistan, Kirgizia, and Siberian platform which had been limitedly or not studied before. The most important among them are the field atlases on the Upper Silurian brachiopods of Kirgizia (1949), and on the Ordovician and Silurian fauna of the Siberian platform (1955), as well as *Atlas of Guide Forms, Vol. II. The Silurian* (*Upper Silurian Brachiopods of the USSR*) (1949).

Her well-known works on Ordovician and Silurian stratigraphy and brachiopods from the Silurian deposits of Podoliya (1954) and the stratigraphy and brachiopods of the Ordovician and Silurian of the Siberian platform (O.N. Andreeva, co-author) became manuals for subsequent generations of paleontologists. The paleontological descriptions, in Nikiforova's works, are very detailed and precise. She was one of the first to study the inner structure of brachiopods using the polished sections technique, and paid a great deal of attention to variability and morphogenesis problems as well as to the analysis of the functional significance of certain structures of the inner skeleton. As a specialist on brachiopods, Nikiforova was one of the authors of the corresponding volume of *Fundamentals of Paleontology* (1960).

Her in-depth research, persistent creative efforts, and devotion to science contributed much to the profound and comprehensive elaboration and solving of fundamental problems, and were supported with solid factual materials. During the subsequent decades, she guided

studies of the reference section of the Silurian and Lower Devonian deposits in Podoliya, as the leader of many lithologists and paleontologists from various cities and institutions of the former USSR who were specialists on the different fauna groups. Nikiforova evaluated the significance of this section for solving certain important problems of the Silurian and Devonian stratigraphy even during her first field trip in 1940. Relevant expeditions lasted up to 1971 and stood as excellent examples of beneficial and successful collective research work, which was more due to the complex techniques applied for studying the reference and stratotype sections.

Nikiforova carried out stratigraphic research on deposits of different ages, from the Ordovician to Devonian. However, the Silurian was her main field of interest, and dominated her research activities. Discussing the lower and upper boundaries of the Silurian in her numerous works and contributions, she passionately argued for the integrity of this subdivision and the nomenclature of its stratigraphic units. Her attention was focussed specifically on the controversial problem of the Silurian-Devonian boundary, which was the subject of the International Symposium accompanied by an excursion to observe sections in the Dniester River region (1968). The authority of Nikiforova as an expert on the Silurian was recognized world-wide. She was the editor and author of generalizing reviews on the stratigraphy and paleogeography of the Silurian deposits in our country in works such as the *Dictionary on Stratigraphy of the USSR* (1956), the summary section in the monograph "Geological Structure of the USSR" (1958), a series of lithologo-paleogeographic maps of the Silurian (1963), and the volume *The Silurian*, of the multivolume *Stratigraphy of the USSR* (1965). In 1968 she gained a doctorate on the basis of the work "The Silurian and its Subdivisions in the USSR." Recognized as the leader of the scientific school which she herself had created, Nikiforova contributed much to the activity of interdepartmental and international geological organizations. She visited Poland, Czechoslovakia, Germany, Belgium, and Canada, where she demonstrated progress in Russian science.

Throughout her long scientific life, Nikiforova was also involved in consulting activities; she trained young paleontologists, and guided the work of specialists from regional geological organizations. Nikiforova imparted her rich scientific experience to her disciples, who work in various parts of the former USSR. She was careful and scrupulous in her work and demanded the same from her disciples. As an expert, she thoroughly investigated problems, and her inferences were well-argued and convincing. She also appreciated these features in the work of her colleagues, and would not stand for premature, insufficiently substantiated opinions and conclusions. She was a very hard-working and persistent person, and at first sight she may have seemed strict, dull, and even severe. However, in reality she was a beautiful woman, and an interesting and nice companion; she was interested in classical literature and art; at home she was a hospitable hostess and fond of gardening. She could prepare remarkable arrangements of flowers, some of which were awarded prizes at exhibitions.

Her long and fruitful scientific activity was rewarded by numerous governmental orders and medals.

Olga Ivanovna Nikiforova lived a long life, filled with unremitting toil. Her death is an irreparable loss for science and for the people who knew her well. She will forever remain in our hearts, and her contribution to the development of paleontology and stratigraphy will promote the further advancement of our science.

B.S. Sokolov, A.I. Zhamoida, T.L. Modzalevskaya, A.F. Abushik, N.N. Predtechenskii, T.N. Koren', A.Ya. Berger, O.P. Kovalevskii, S.V. Cherkesova, E.V. Vladimirskaya, V.D. Chekhovich

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